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TITANIUM IN AEROSPACE APPLICATIONS

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Introduction

Titanium was earmarked as a prime material for aircraft from the start, but the initial impetus in research and development of titanium in the United States came from Army Ordnance. However, its potential was recognized by the aeronautical industry, and the major application has been in military aircraft. A significant amount has gone into commercial aircraft, chiefly jet engines, and it is finding increasing application in the aerospace field. This trend is illustrated by the 1960 production breakdown by application, Table 1.

TABLE 1. ESTIMATED 1960 TITANIUM CONSUMPTION BY APPLICATION

Application	Consumption, per cent
Military aircraft	65
Commercial aircraft	13
Missiles/space	17
Chemical	3
Ordnance	2

Titanium is a relatively high-cost specialty metal whose selection in aeronautical applications over less-costly materials depends on its value in terms of weight savings, longer life, or lower operating cost. The purpose of the present paper is to review the past and current status of titanium in aeronautical applications, including pertinent design criteria, available titanium products and alternative materials, and fabrication problems. Finally, the future possibilities for titanium are considered.

*This memorandum is based on a paper presented on May 30, 1961, at the Fifth International Aeronautical Convention of A.F.I.T.A. in Paris. Because of its general interest, it is being distributed by DMIC. Dr. Jaffee is associated with Battelle Memorial Institute; Mr. Sharp was formerly connected with Pratt & Whitney Aircraft Division of United Aircraft Corporation, and is now a Consultant, 721 Main Street., Hartford, Connecticut; and Mr. Nycum is with Titanium Metals Corporation of America, New York, New York.

Production

The bulk of the titanium sponge produced in the Free World was from the United States, as indicated by Table 2. Japan, England, and France produced smaller quantities of sponge. At its peak, the United States titanium industry reported an annual capacity of about 28,000 tons, comprised of Du Pont. Cramet (Crane Company and Republic Steel), Dow Chemical, Electromet (now Union Carbide Metals), and Titanium Metals Corporation of America. More recently, National Distillers (Reactive Metals) placed a sponge plant on stream.

The course of sponge capacity, production, and price of titanium since the first commercial sponge was announced by Du Pont in 1949 through 1960 is shown in Figure 1. Ingot production is higher than sponge production as a result of scrap utilization and importation. The price of sponge has decreased steadily from $5 per pound in 1954 to the present price of $1.60 per pound in the spring of 1961. At the same time, the price of mill products, as reflected by a composite index (based on the cost of sheet and strip, bar, and billet, commercially pure and alloy grades, plus size and quantity extras), decreased from $15.25 per pound in 1954 to $6.97 per pound in 1960.

The initial growth of the titanium industry in the United States was largely subsidized by the Government through construction loans, purchase commitments, accelerated tax amortization, and research and development grants. The steeply rising curve of sponge and mill products through 1956 reflects the response of the titanium industry to this subsidization. The production status achieved by titanium in less than 10 years required 26 years for magnesium, 28 years for aluminum, and 40 to 80 years for copper, lead, and zinc. However, in 1956, subsidation virtually ceased, and by 1957, military aeronautical attention shifted from manned aircraft to missiles. As a result of the ensuing cutbacks and stretchouts of military-aircraft orders, titanium mill-product production took a precipitous drop from its high-water mark of 11,300,000 pounds in 1957 to 5,100,000 pounds in 1958. Sponge production dropped from 35,500,000 pounds in 1957 to 7,800,000 pounds in 1959. By 1958, both the Dow and Cramet plants halted production. In 1959, Union Carbide's plant went on standby. As a result of increased consumption of titanium in missiles (17 per cent), commercial aircraft (13 per cent), and chemical applications (3 per cent), the titanium industry made a strong comeback in 1959 and 1960, with 1960 mill-product shipments of 10,100,000 pounds almost equaling the peak production year of 1957. In the first quarter of 1961, 3,310,000 pounds of mill products were shipped, which corresponds to an annual rate of 13,300,000 pounds. Companies producing sponge in 1960 included TMCA, Du Pont, and Reactive Metals. It is perhaps unique in metal production that, throughout the period of declining production, the price of titanium sponge and mill products decreased steadily.

Mill-product shipments in the decade 1951 to 1960 are shown in Table 3. The high percentage of bar and billet relative to flat rolled products reflects the high consumption in aircraft jet engines. While the flat-rolled tonnage has been less, the dollar value of this type of product has been close to, or in some years greater than, the dollar value of bar and

TABLE 2. FREE-WORLD TITANIUM-SPONGE PRODUCTION
(Short Tons)

Year	USA	Japan[a]	England	Others
1948	10[b]	-	-	-
1949	25[b]	-	-	-
1950	75[b]	-	-	-
1951	495	-	-	-
1952	1,075	9	-	-
1953	2,241	77	-	-
1954	5,370	673	-	-
1955	7,398	1,368	(c)	-
1956	14,595	2,768	1,700	(d)
1957	17,249	3,393	1,700[b]	NA[e]
1958	4,585	1,812	1,300[b]	NA[e]
1959	3,898	2,730	1,300[b]	NA[e]
1960	5,490	2,538	(f)	(f)

(a) Japanese sponge producers include Osaka Titanium, Toho Titanium, and Nippon Soda.

(b) Estimated.

(c) ICI began production from new plant in August, 1955, and was operating at a 1,700-ton rate by the end of the year.

(d) France achieved 153 tons capacity; one plant 140 tons per year, another 13. Production for the year unknown.

(e) NA = not available.

(f) It is understood that neither ICI's sponge plant in England nor the sponge plant in France in which Pechiney has an interest were operated in 1960.

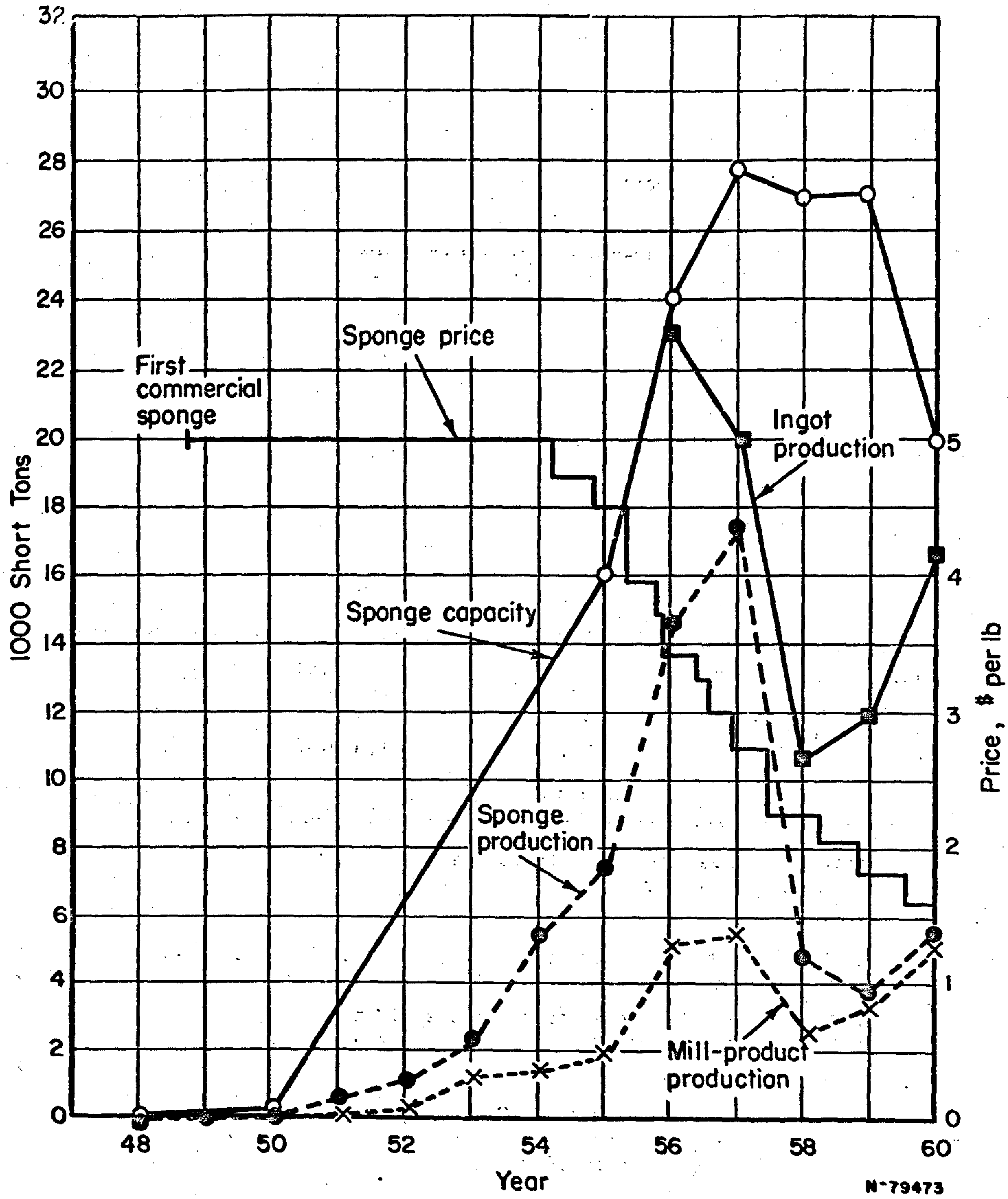

FIGURE 1. TITANIUM PRODUCTION STATISTICS

TABLE 3. TITANIUM INDUSTRY SHIPMENTS BY MAJOR PRODUCT CLASSIFICATION (1951-1960)

(In Pounds)

Year	Flat-Rolled	Bar and Billet	Totals
1951	NA[(a)]	NA[(a)]	170,000
1952	NA[(a)]	NA[(a)]	280,000
1953	NA[(a)]	NA[(a)]	2,200,000
1954	NA[(a)]	NA[(a)]	2,600,000
1955	1,800,000	2,200,000	4,000,000
1956	3,200,000	6,900,000	10,100,000
1957	3,600,000	7,700,000	11,300,000
1958	2,000,000	3,100,000	5,100,000
1959	1,900,000	4,500,000	6,400,000
1960	2,000,000	8,100,000	10,100,000

(a) NA = not available.

billet. The economics of these two product groups is such that, for some applications, such as rocket motor cases which can be made either from forgings or plate, there has been a swing to the forging approach because of both engineering reasons and price difference.

Initially, mill products were produced in the United States by Titanium Metals Corporation of America (50 per cent owned by Allegheny Ludlum and 50 per cent by National Lead Company), Rem-Cru (50 per cent owned by Remington Arms and 50 per cent by Crucible Steel), Mallory-Sharon Titanium (50 per cent owned by P. R. Mallory and 50 per cent owned by Sharon Steel), and Republic Steel. Titanium Metals Corporation of America and Republic Steel are basically unchanged in their mill product organizations, but Rem-Cru now operates as a division of Crucible Steel (Remington Arms having sold its half interest to Crucible), and Mallory-Sharon now operates as Reactive Metals Corporation. This company is now owned by National Distillers and Sharon Steel, and has expanded its operations to include production of zirconium.

In addition to these four companies, Harvey Aluminum and Oregon Metallurgical Company have entered the titanium mill-product enterprise--Harvey specializing in bar, billet, and extruded-shape products, while Oregon Metallurgical specializes in ingot and titanium castings.

Production of titanium mill products outside of the United States has pretty much fallen into the following groups: in England, Imperial Chemical Industries and Jessop; in West Germany, Continental Titanium Metals Corporation (50 per cent owned by Deutsche Edelstahlwerke and 50 per cent owned by Titanium Metals Corporation of America) and Krupp; and in Japan by Kobe Steel, Suitono Light Metal Industries, and Furukawa Magnesium.

In the course of its short history, the titanium industry has faced a number of problems, among which may be cited the following:

(1) <u>Sponge Quality</u>. Initially, sponge was produced with a hardness of 240 Brinell, which caused considerable difficulty in production of ductile titanium products. Today, sponge can be produced with a hardness as low as 80 Brinell, and impurities such as oxygen sometimes are intentionally added to bring the strength of the metal to ranges desired (a practice not condoned for critical applications involving notch sensitivity).

(2) <u>Ingot Melting</u>. Considerable difficulty was encountered in attaining homogeneity in early single-melted ingots. The practice of consumable-electrode arc remelting led to homogeneous ingots that now are up to 30 inches in diameter--weighing 8 to 10,000 pounds. Significantly, the titanium double-melting practice now frequently is specified for steels and superalloys where high purity and homogeneity are desired.

(3) Hydrogen Contamination. Hydrogen was found to embrittle titanium products, and some early application failures were traced to this source. The use of vacuum-melting procedures, instead of melting under inert gas atmospheres, permitted removal of hydrogen below embrittling levels. Thus, the double-vacuum-melting practice solved two of the three major problems of the titanium industry's early days.

(4) Stress Corrosion. Titanium and its alloys were evaluated for stress-corrosion susceptibility in all conventional media and were found to be susceptible only in anhydrous red-fuming nitric acid. Subsequently, the susceptibility of titanium to hot-salt stress corrosion above 600 F came to light. Control of this problem is being accomplished by maintaining a clean surface on titanium products during stress relieving, and by maintaining elevated-temperature service stresses below the threshhold level. For higher temperatures, both alloy composition and surface coatings show promise for minimizing this problem.

(5) Idle Capacity. This is one of the major problems of the industry today. Up to 1957, the industry expanded and re-expanded to meet production goals thought necessary for military objectives. Supply was so tight that titanium was allocated according to priority, and only 10 per cent was released for nondefense applications. After the weapon-systems reappraisal in 1957, the situation reversed, and in November, 1957, the industry was operating at about 4 per cent of capacity. Now, although production has risen again, overcapacity continues to plague the industry.

Titanium Alloys

Detailed properties of titanium alloys will be presented in later discussions of design criteria pertinent to the selection of titanium for various applications. At this point, it is sufficient to mention the various commercial, semicommercial, and advanced experimental alloys, and to comment briefly on their status.

Table 4 illustrates the relative production of the various alloy products in 1960. Ti-6Al-4V and Ti-5Al-2.5Sn dominate alloy consumption because of their extensive application in jet-engine compressors, the major application for titanium. Two sheet alloys, Ti-8Mn and Ti-2Fe-2Cr-2Mo, are used extensively in airframe applications. A new heat-treatable forging

TABLE 4. ESTIMATED CONSUMPTION OF TITANIUM MILL PRODUCTS IN 1960

(In Pounds)

Alloys	Flat Rolled	Bar and Billet
Commercially pure	900,000	725,000
Ti-6Al-4V	350,000	6,000,000
Ti-5Al-2.5Sn	400,000	875,000
Ti-4Al-3Mo-1V	30,000	-
Ti-13V-11Cr-3Al	30,000	40,000
Ti-8Al-1Mo-1V	-	40,000
Ti-7Al-4Mo	-	90,000
Ti-8Mn and Ti-2Fe-2Cr-2Mo	250,000	-
Ti-6Al-6V-2Sn	-	170,000
Ti-5Al-4FeCr	40,000	60,000
Total	2,000,000	8,000,000

alloy, Ti-6Al-6V-2Sn is being used in the Davy Crockett recoilless-rifle weapon system, and a significant amount of this alloy was used in 1960. Ti-7Al-4Mo, an alpha-beta alloy with potential in jet engines and heat-treated forgings, and the beta alloy, Ti-13V-11Cr-3Al, with potential in the solid-motor case field, were produced only in nominal amounts. The relatively low consumption of the newer titanium alloys should not be considered a reflection on their merit. Production application of a material requires a lead time of from 2 to 3 years, and current production reflects material selections made several years ago.

Alpha Alloys

Ti-5Al-2.5Sn is the only production alpha alloy. It is used extensively in sheet form where weldability, good low-temperature ductility, and moderate creep resistance (up to about 900 F) are desired. As Table 4 shows, Ti-5Al-2.5Sn also was used extensively in bar and billet form.

A large number of alpha alloys with somewhat higher strength at elevated temperature have been developed. These have not been used extensively, primarily because applications requiring the higher temperature capability are not yet in production. The advanced alpha alloys arranged in order of increasing elevated-temperature creep-strength capability are listed below:

Ti-8Al-2Cb-1Ta

Ti-8Al-1Mo-1V

Ti-5Al-5Sn-5Zr

Ti-7Al-12Zr

Ti-8Al-8Zr-1CbTa.

High-strength alpha-alloy development is based on the practice of using the highest aluminum content possible while avoiding thermal instability from formation of the ordered α_2 phase (Ti_3Al). Zirconium has been useful in such alloys because it is soluble in the alpha phase without participating in the ordering reaction. Tin forms an ordered phase of the Ti_3X type. It acts in conjunction with aluminum, and is equivalent to about 1/3 per cent aluminum per 1 per cent tin. Small amounts of beta-stabilizing elements like columbium, tantalum, molybdenum, and vanadium, have a moderating effect on the instability reaction, and permit somewhat higher aluminum content without instability, but they also are detrimental to creep strength.

For the alloys with increased creep strength at higher temperatures, problems with instability and susceptibility to salt-corrosion attack also increase. For this reason, the Ti-8Al-8Zr-1CbTa alloy has been withdrawn from a number of potential applications. The Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr alloys are being developed as part of an extension of the Government-supported Titanium-Sheet-Rolling Program.

Alpha alloys characteristically are not heat treatable, although the Ti-8Al-1Mo-1V alloy can be strengthened to a moderate extent by beta quenching followed by alpha-beta tempering. Duplex heat treatment of Ti-8Al-1Mo-1V alloy, consisting of a high alpha-beta (1800 F) anneal, air cool, and low alpha-beta (1100 F) reheat, is beneficial in regard to creep resistance but at a sacrifice of tensile ductility. The straight-alpha alloys, Ti-7Al-12Zr and Ti-5Al-5Sn-5Zr, have optimum creep resistance and tensile ductility in the alpha-annealed (1600 F) condition.

Future developments in the high-aluminum alloys may be expected in high-aluminum Ti-Al-Cb- and Ti-Al-V-type alloys, where fabricable compositions with 10 to 14 per cent aluminum and 15 to 50 per cent beta stabilizer have been developed on a laboratory scale. These alloys exhibit interesting elevated-temperature strength at some sacrifice of room-temperature ductility. Little is known concerning their creep strength, creep stability, and long-time oxidation resistance.

Alpha-Beta Alloys

The first titanium alloys developed were of the aluminum-free, beta-stabilized, alpha-beta type, characterized by Ti-8Mn and Ti-2Fe-2Cr-2Mo. These are excellent sheet alloys, with good formability. They generally are not welded or heat treated and find application in airframe structures requiring reasonable strengths up to about 600 F.

Heat treatability was desired in alpha-beta sheet alloys that would be supplied in the soft solution-treated condition and hardened by a simple aging treatment after forming. These "formageable sheet-rolling alloys" were developed under the auspices of the U. S. Government-supported sheet-rolling program. The alpha-beta alloys originally in the program included the following:

Ti-4Al-3Mo-1V

Ti-2Al-6Mo

Ti-2.5Al-16V

Ti-6Al-4V.

Later, Ti-2Al-6Mo was dropped because it showed little formability advantage over Ti-4Al-3Mo-1V. Beta alloy, Ti-13V-11Cr-3Al, was added at a later stage. Ti-6Al-4V alloy sheet was included in the original program, although its high aluminum content precluded a very soft solution-treated condition. Another sheet alloy of similar characteristics, Ti-5Al-2.75Cr-1.25Fe, was not in the sheet-rolling program.

In Phase I of the Sheet Rolling Program, on production of heat treatable titanium alloy sheet, remarkable success was achieved in developing production-type procedures for producing flat solution-treated sheets. Of the many procedures investigated, a roller-leveler quenching device appears to have emerged as the best. Phase II of the sheet-rolling program was

concerned with design-criteria data. Phase III was devoted to fabrication of typical airframe components. In this phase it was learned that the spring-back in room-temperature forming was a severe problem. The original concept of room-temperature forming followed by simple aging had to be abandoned for all but the simplest parts. While it has been determined that the bulk of the forming operations, such as bending and stretching could be performed at room temperature, final hot sizing was incorporated for geometrical uniformity. This did not result in sacrifice in the heat-treated properties. Since hot forming is necessary in many cases, designers of supersonic airframes are turning their attentions to near-alpha alloys, like Ti-8Al-1Mo-1V, which have high annealed strength.

In forging alloys, Ti-6Al-4V has been used extensively. This near-alpha alloy has moderately good elevated-temperature strength, hydrogen tolerance, heat-treatment response, weldability, and low-temperature notch ductility. Its lack of adverse properties probably is the key to its success. Ti-4Al-4Mn is an alpha-beta alloy of roughly the same characteristics as Ti-6Al-4V, but it has lost favor in many applications, possibly because of difficulty in maintaining control of manganese during melting.

Ti-7Al-4Mo is an alpha-beta forging alloy with a capability of somewhat greater elevated-temperature strength and deeper heat-treatment hardening response than Ti-6Al-4V. It is taking over some of the jet-engine applications, particularly where higher Mach numbers are anticipated. Other alpha-beta alloys, including Ti-5Al-1.5Fe-1.4Cr-1.2Mo, Ti-6Al-6V-2Sn, and Ti-5Al-4FeCr, have been used in limited quantity for heat-treated forgings. These alloys permit considerably greater strengthening and greater depths of hardening than are possible with Ti-6Al-4V.

Except for the rich alphas of the Ti-6Al-4V type, the alpha-beta alloys generally are not used when fusion welding is involved. Alpha-beta alloys as a class tend to lack low-temperature ductility and notch properties. Ti-6Al-4V contains about the most beta that can be tolerated for good cryogenic properties.

Beta Alloys

Despite the wealth of alpha and alpha-beta alloys that have been developed, only one beta alloy has emerged on a production basis, Ti-13V-11Cr-3Al. This alloy is sufficiently rich in beta-stabilizing elements, supplemented by the transformation-retarding influence of aluminum, that it can retain its beta structure after slow air cooling from the beta field. Upon subsequent aging, it can be heat treated to high strength levels with quite useful ductility. As a result of its sluggish reaction kinetics, the alloy is ductile in the as-welded condition, even in heavy sections. The beta alloy is of considerable interest for heat-treating and welding applications in both sheet and heavy forgings. Its chief limitations are long-time thermal instability above 600 F, poor notch ductility at cryogenic temperatures, and brittle welds after aging.

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Future development of beta-type alloys appears to be a potential field for research. The directions of interest include use of strain transformation to martensite and precipitation hardening from the beta phase.

Design Criteria

The selection of titanium for aerospace applications over alternative materials generally is dictated by economic consideration of how much it is worth to save a pound of weight or to increase the life of the component concerned. The value of weight savings in space applications has been estimated from $25 to several hundred dollars per pound, with $50 a frequently adopted figure. The value depends on whether the mission is civilian or military and on the criticality of the component. The value chosen may then be compared with the cost increment of using titanium per pound of weight saved, and a decision made as to whether the selection was justified.

Density

Density is a primary design criterion in all applications, structural and otherwise. Figure 2 shows the density of metals plotted against melting point. The lower locus of density-versus-temperature for solid metals connects magnesium, beryllium, titanium, vanadium, columbium, molybdenum, tantalum, and tungsten. For any given temperature, the lowest density material would be selected, assuming other factors are equal. However, other factors are not equal. For example, because of high cost, consideration of beryllium for a nonstructural application would be feasible only in unusual circumstances. In the case of vanadium, both cost and the lack of corrosion resistance at elevated temperatures limit the potential uses. Depending on the length of exposure, titanium is used from 500 F to 2000 F in nonstructural applications where density is the primary design criterion.

For long-time service, the upper limit for titanium in hot air is about 1000 F. In short-time applications, such as fire walls, titanium is considered useful to 2000 F. In marine environments, titanium may be taken to be completely impervious.

Elastic Deformation

The stiffness of compression-loaded structures often is governed by modulus-density considerations, with the ratio of square root of modulus to density, $\sqrt{E}/\rho$, being a useful structural index for elastic buckling of columns. The index for elastic buckling of sheet is $\sqrt[3]{E}/\rho$. Although, on the basis of E/ρ, steel and titanium are at a par with values of about 1,000,000, the square root and cube root indexes make low-density titanium advantageous over steel for use in structures critical to elastic buckling. In the design of compression structures involving the possibility of plastic buckling, the parameter of crippling stress to density (F_{cr}/ρ) governs.

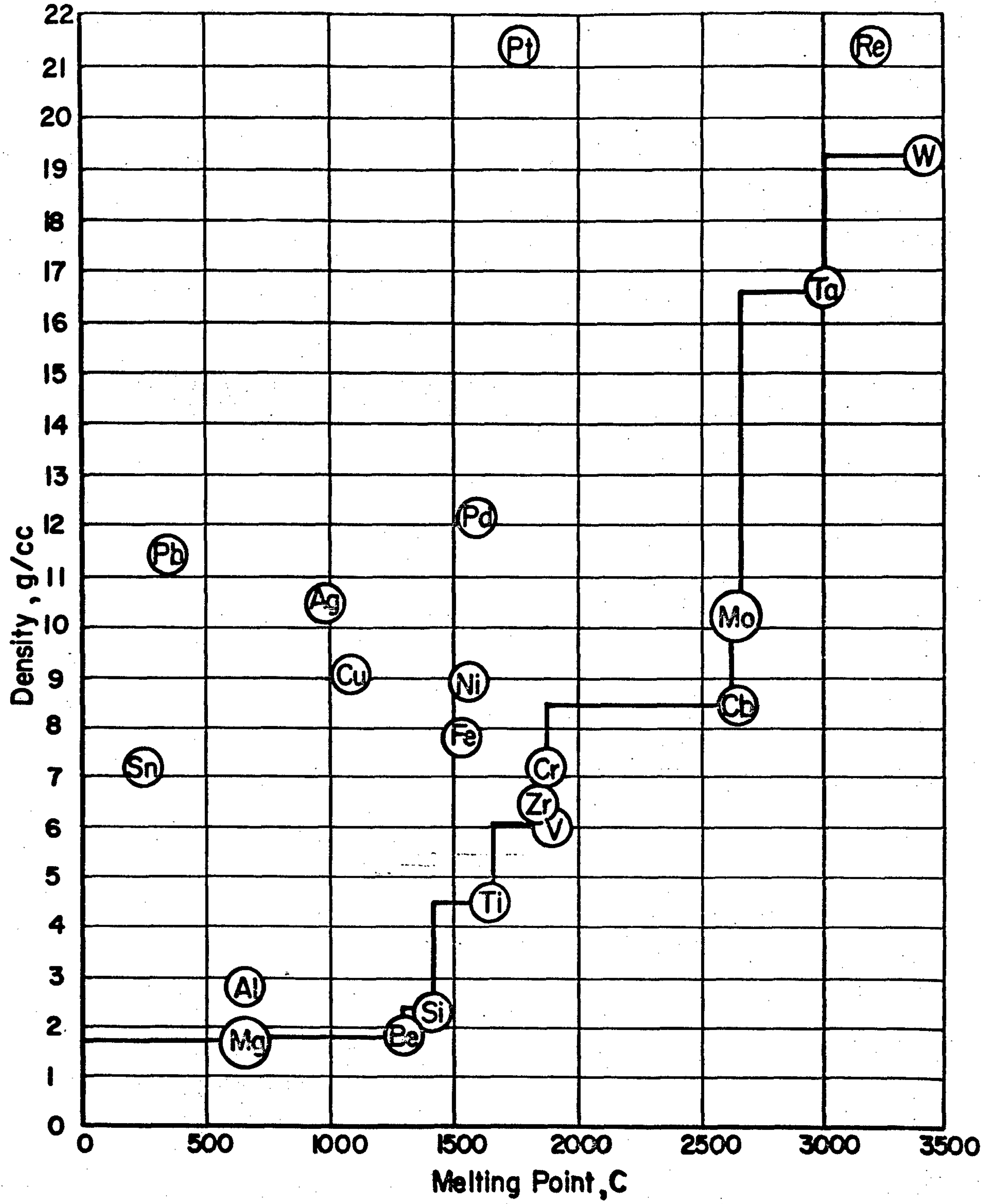

FIGURE 2. DENSITY-MELTING POINT RELATIONSHIP OF METALS

Structures that are compression critical often will be subject to a minimum acceptable gage limitation; in this case, the material with lower density generally proves advantageous.

Strength-Weight

The strength-weight ratio applies as a criterion under conditions of short-time loading or in cases where long-time load capability is controlled by the yield strength (up to about 500 F for most titanium alloys).

Most of titanium's structural applications have been based on excellent strength-weight performance. Figure 2 compares titanium alloys with three classes of steel and an aluminum alloy on a tensile-strength and tensile strength-density basis. Data are not included for annealed alloys with less than 10 per cent elongation and for heat-treated alloys with less than 5 per cent elongation. Titanium alloys attain strength-weight ratios of 0.8 to 1.2 million psi at room temperature, which decrease to about 0.6 to 0.9 million psi at 800 F. The stronger titanium alloys have higher strength-weight ratios than the strongest steel shown.

The elevated-temperature strength-weight ratios of various titanium alloys are illustrated in Figure 4. In the lower temperature range, the beta alloy has the highest short-time properties, alpha-beta alloys are intermediate, and alpha alloys lowest. However, the alpha-type alloys maintain their strength better at temperatures above 800 F. An experimental high-aluminum alloy, Ti-10Al-15Cb, exhibits structural properties to about 1400 F.

The effect of low temperatures on the strength-weight ratio of titanium alloys, compared with steels, is illustrated in Figure 5. It is seen that the strength-weight ratio of titanium alloys increases to above 1.5 million psi at liquid-hydrogen temperature. High strengths at very low temperature make titanium alloys attractive for cryogenic pressure vessels.

Creep

Under long-time loading above 500 F, rupture and creep are the applicable design criteria for titanium alloys. Figure 6 presents 100-hour rupture curves for various metallic materials. These data show that titanium alloys maintain good rupture properties up to about 1000 F and are intermediate in rupture performance between ferritic and austenitic steels.

More often, actual creep strain is used in design in creep-critical applications. Figure 7 illustrates the creep strength of alpha-titanium alloys for 0.1 to 0.2 per cent plastic deformation in 150 hours, a criterion which is used in designing gas-turbine-compressor components. It is seen that creep strengths above 25,000 psi are exhibited by two advanced alpha-type alloys, Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr. High creep properties also are shown by the near-alpha Ti-8Al-1Mo-1V alloy.

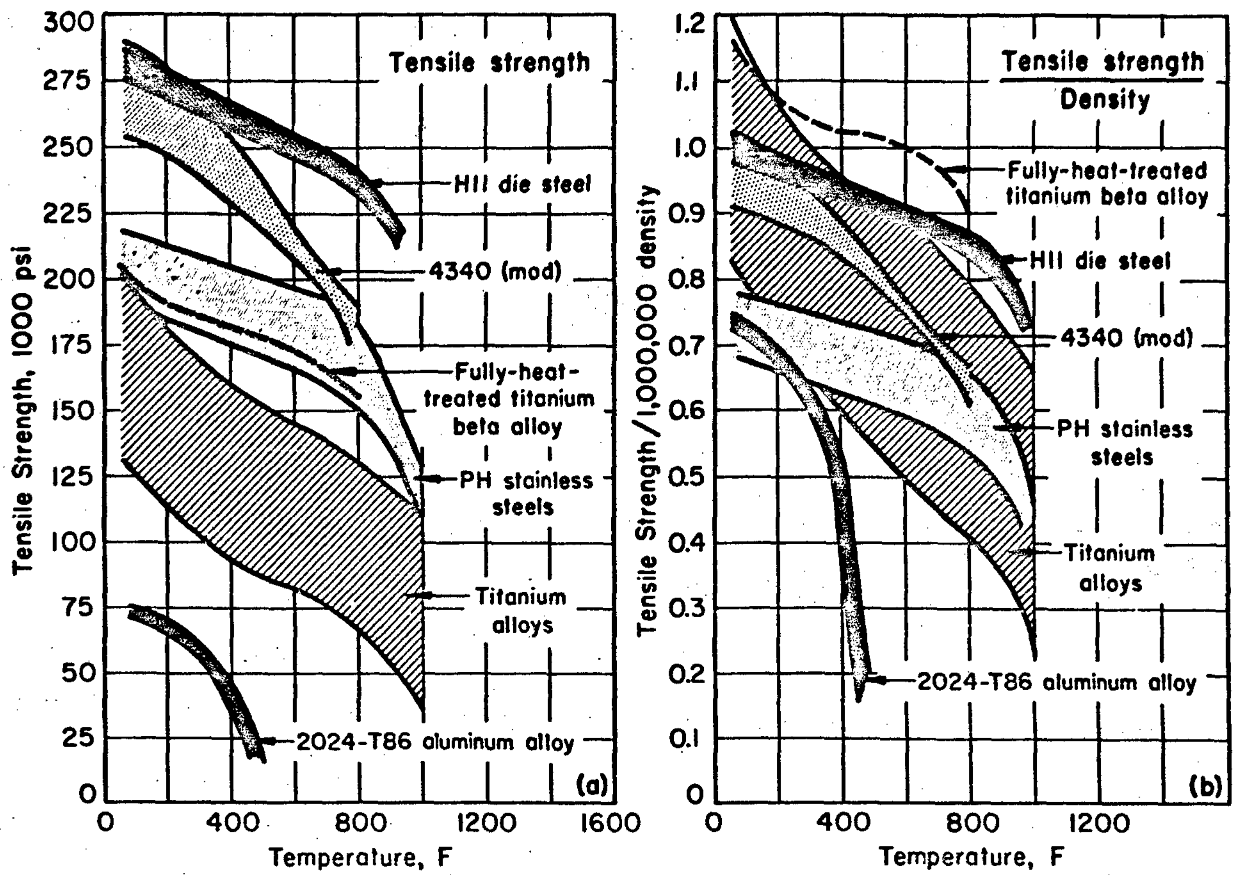

FIGURE 3. COMPARISON OF SHORT-TIME TENSILE STRENGTH AND TENSILE STRENGTH/DENSITY RATIO FOR TITANIUM ALLOYS, THREE CLASSES OF STEEL, AND 2024-T86 ALUMINUM ALLOY

(ASM Handbook)

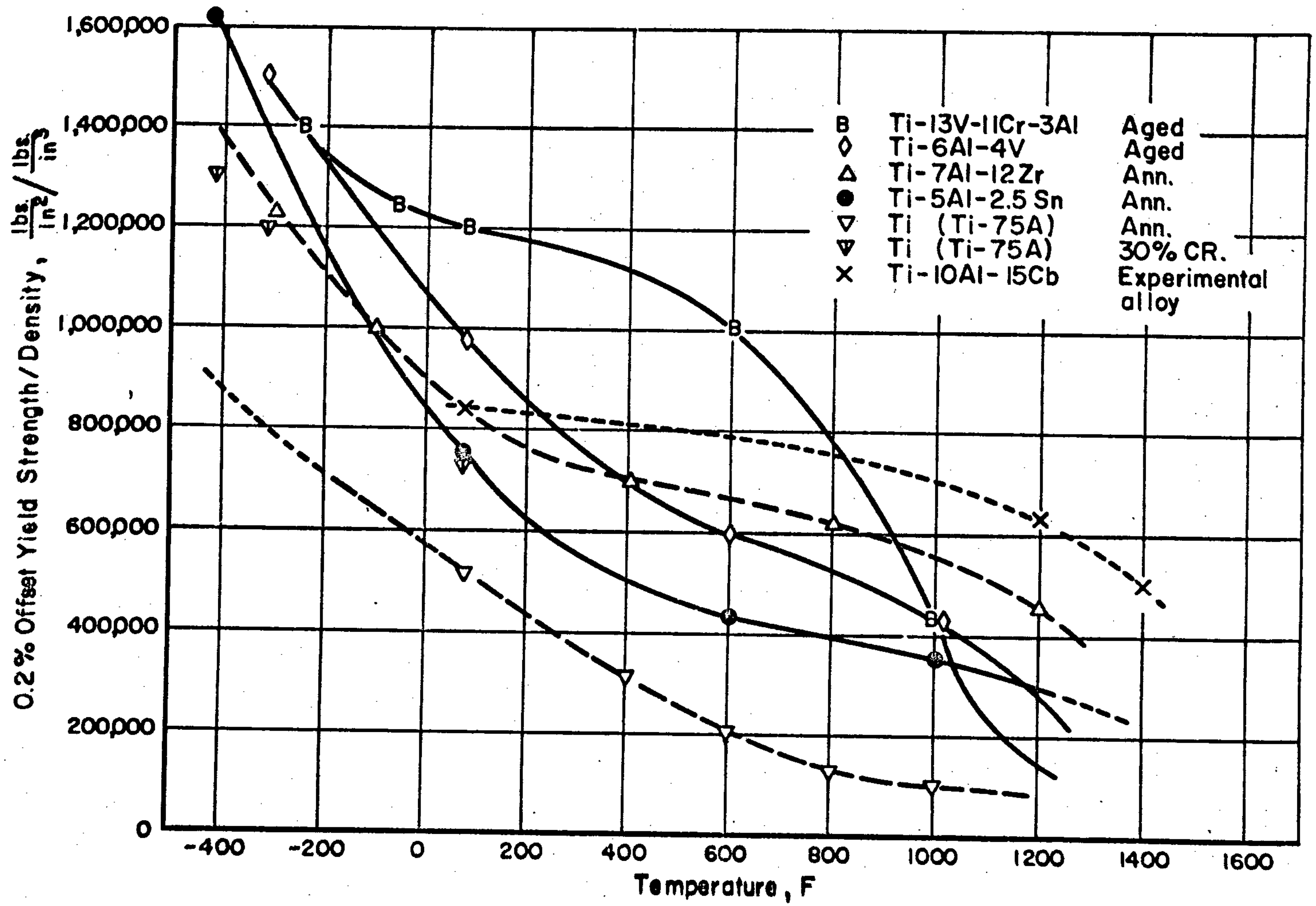

FIGURE 4. EFFECT OF TEMPERATURE ON THE STRENGTH/WEIGHT RATIO OF TITANIUM ALLOYS

(Compilation of selected data from TMCA, Crucible, WADC TR 58-386, WADD TR 60-254, ARDC TR 59-66, Convair Astronautics, AMC TR 58-7-574, General Electric, Reactive Metals, and Republic Steel Corporation.)

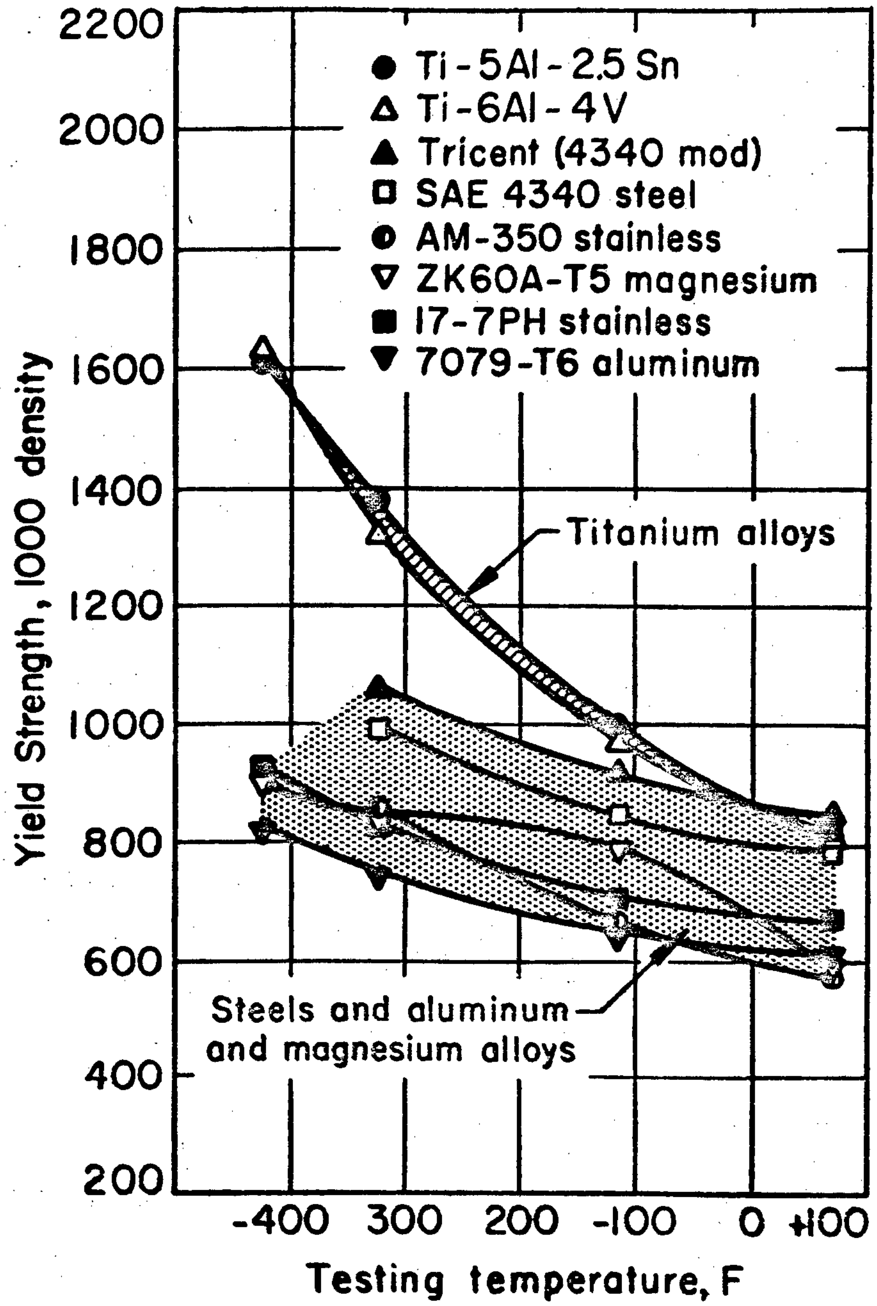

FIGURE 5. YIELD STRENGTH/DENSITY FOR TWO TITANIUM ALLOYS AND OTHER MATERIALS AT CRYOGENIC TEMPERATURES

(ASM Handbook)

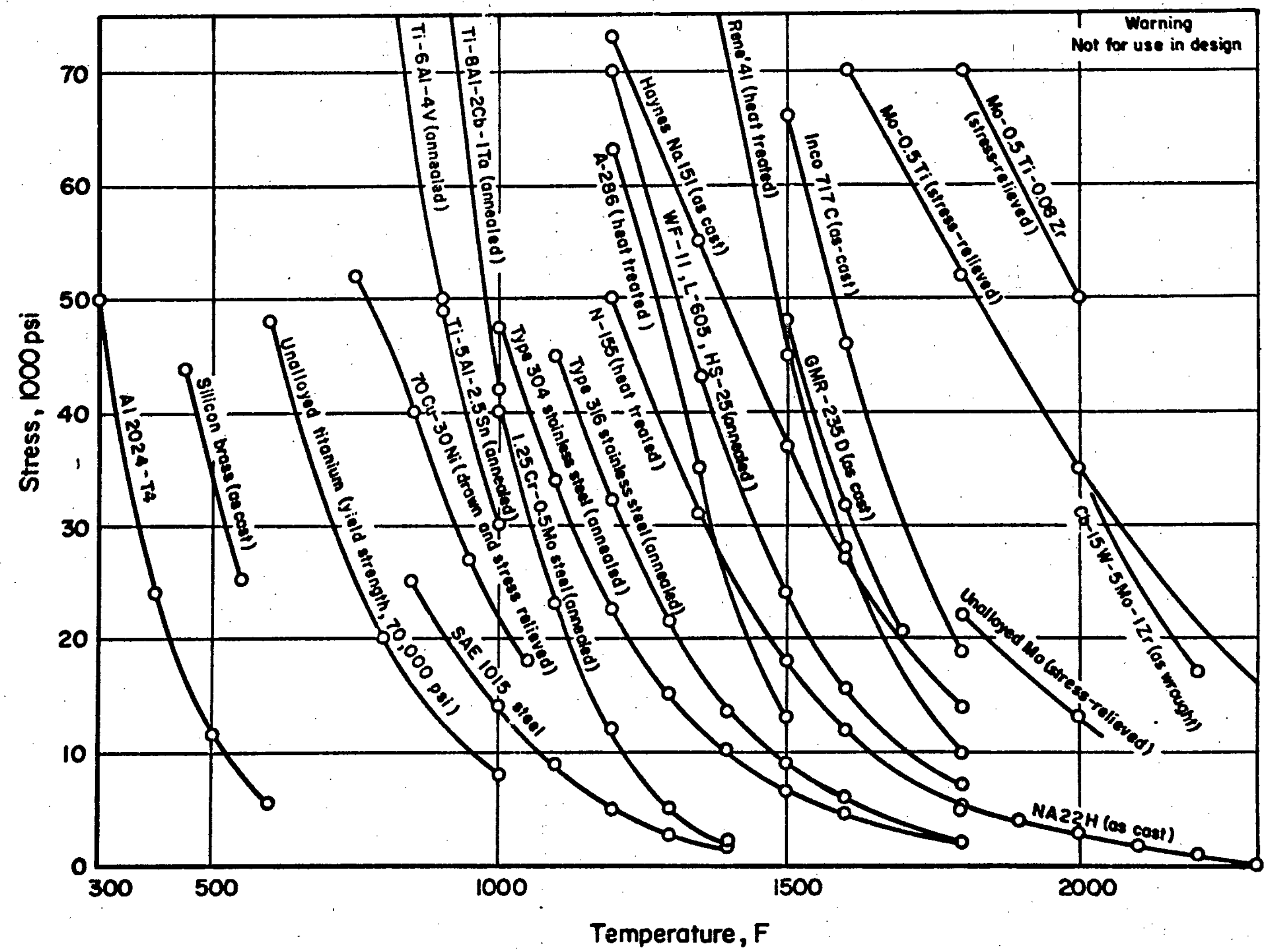

FIGURE 6. STRESS-VERSUS-TEMPERATURE CURVES FOR RUPTURE IN 100 HOURS FOR SELECTED ALLOYS

(DMIC Memo No. 92, March 23, 1961)

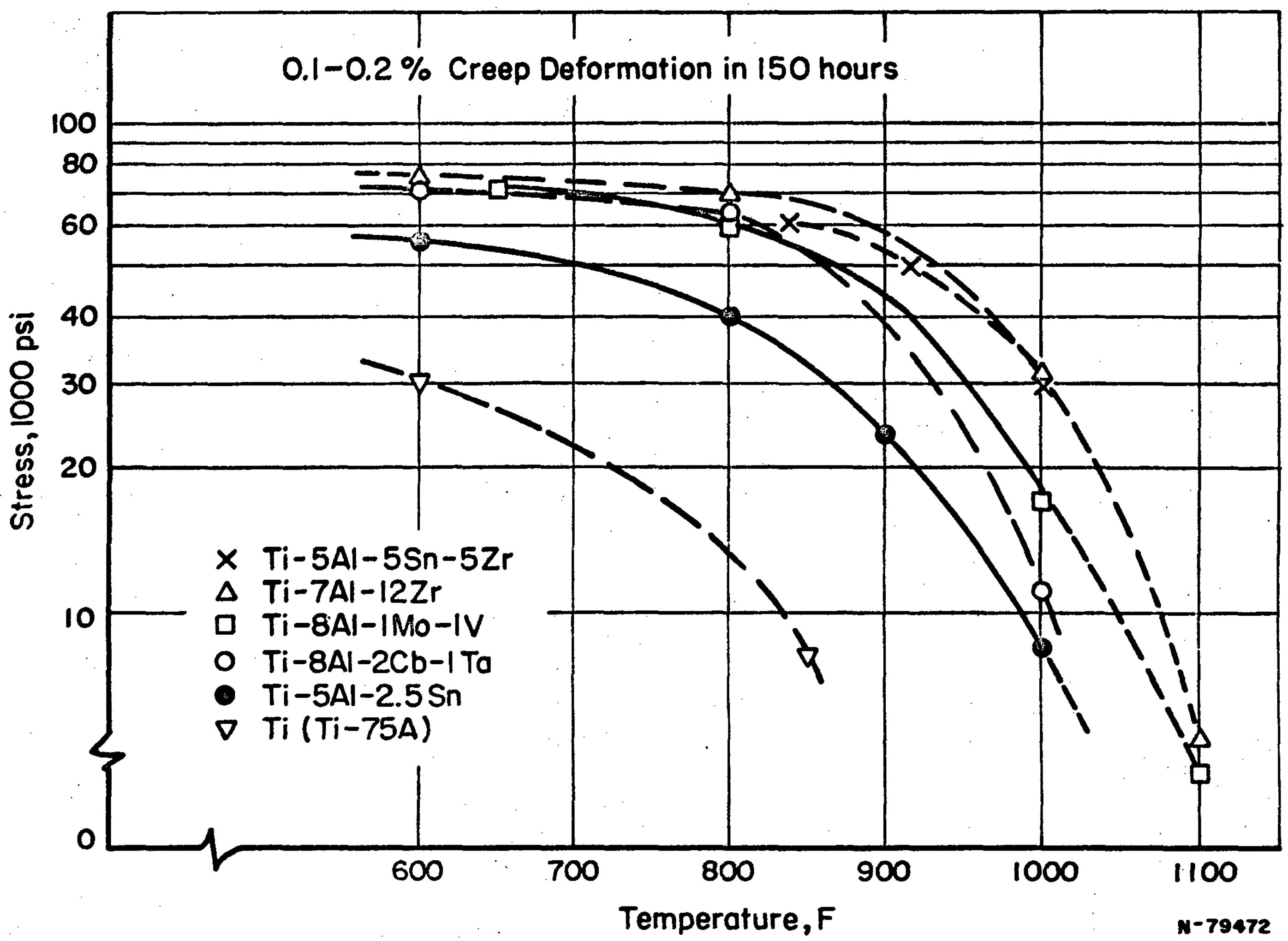

FIGURE 7. CREEP STRENGTH OF ALPHA-TITANIUM ALLOYS IN THE ANNEALED CONDITION

(Compilation of selected data from TMCA, Crucible, Mallory Sharon (Reactive Metals), and TML Report No. 82, September 10, 1957.)

Relaxation of titanium alloys under applied stress at elevated temperatures is a manifestation of creep. Relaxation curves for titanium alloys as measured by ability to sustain a bending stress after 50 hours of exposure at various temperatures are illustrated in Figure 8, where the order of resistance is seen to be the same as that of relative creep resistance. Retention of residual stress essentially disappears beyond 1000 F.

Thermal Stability

Thermal stability is a measure of the ability of an alloy to maintain its original properties after elevated-temperature exposure. It is of concern for high-creep-strength titanium materials. Generally, creep-resisting titanium alloys are used in the annealed condition and are of an alpha-type, so that beta transformation is not a source of instability. Of chief concern is a thermal ordering reaction within the alpha phase, which increases with aluminum content. The advanced alpha alloys are designed with aluminum contents adjusted so as not to lose more than about 25 per cent of their original ductility as the result of creep exposure.

Notch Sensitivity

The design of pressure vessels has necessitated serious consideration of the ability of materials to resist fracture in the presence of notches and stress concentrations. The strength of ductile materials generally increases in the presence of a notch as the result of lateral restraint. However, at increasing notch acuities, notch strength decreases again. In the presence of more severe notches, load-bearing capacity becomes less than that of the unnotched material. Figure 9 compares the notch-unnotch strength ratio of titanium alloys with that of several steels. The Ti-6Al-4V heat treated to 140,000 psi tensile strength is an extremely tough material; after heat treatment to 170,000 psi, it becomes more notch sensitive. The energy requirement to propagate a crack, measured by G_c, decreases with increasing strength level for the three titanium alloys as shown in Figure 10. Ti-6Al-4V exhibits somewhat higher G_c's than does the beta alloy at the same strength level.

In cryogenic applications, notch sensitivity plays an important role as a design criterion. Figure 11 shows notched-strength data on edge-notched titanium alloys at temperatures to that of liquid hydrogen. All of the ratios decrease with increasing temperature. However, the alpha alloy, Ti-5Al-2.5Sn, possesses better notch strength than the others, particularly the all-beta alloy. Ti-6Al-4V with low interstitial content also has good notch properties at liquid-hydrogen temperature.

Metallographical condition and interstitial content both are important in low-temperature notch sensitivity as illustrated by Figure 12. The equiaxed structure is less notch sensitive than the acicular, and the interstitial content should be a minimum. Hydrogen makes alpha-beta titanium alloys more notch sensitive, particularly from room temperature to -40, as shown by the minimum in notch strength. Reducing the hydrogen content of the Ti-2Fe-2Cr-2Mo alloy from 70 to 20 ppm hydrogen raises notch strength in this temperature region.

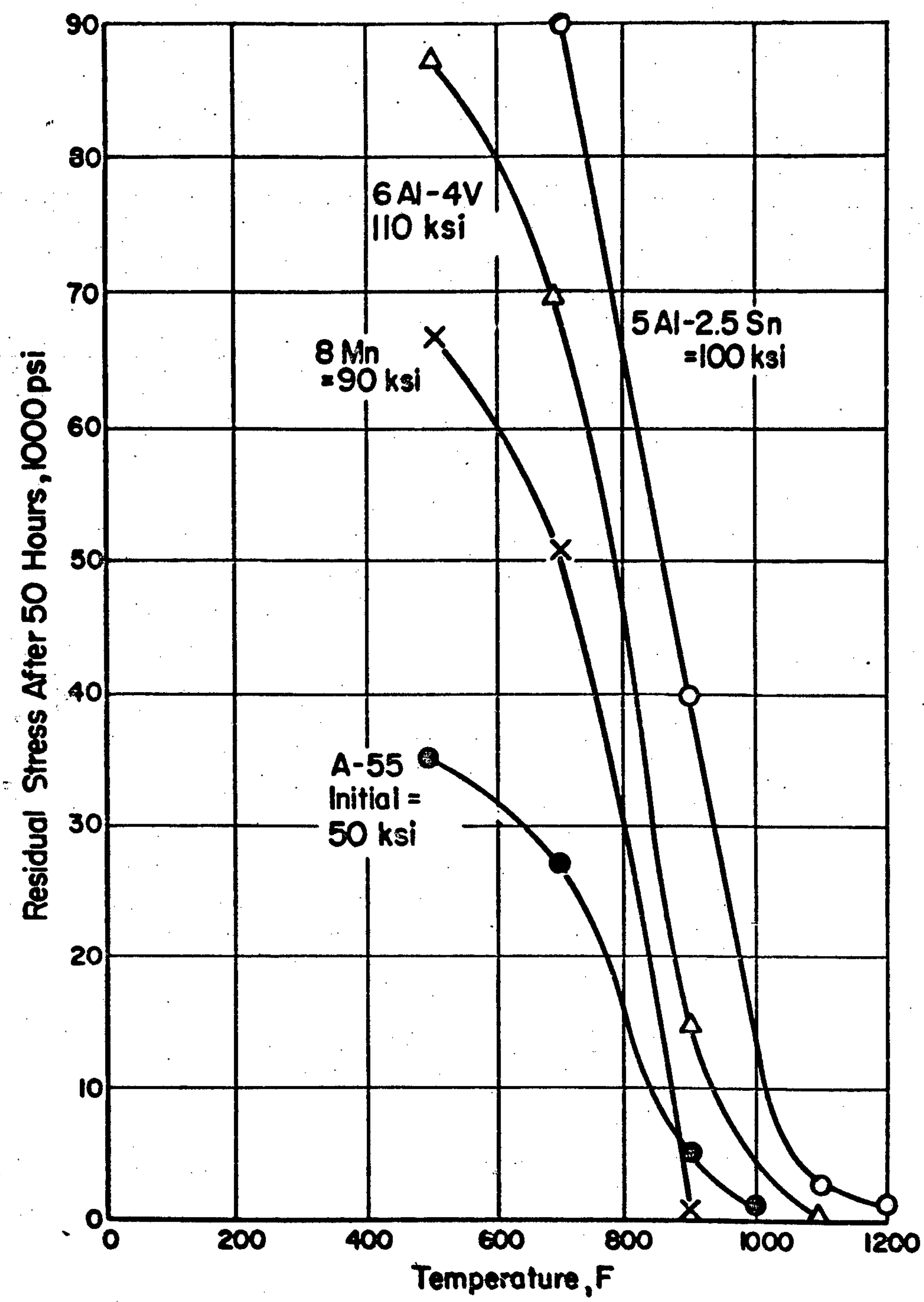

FIGURE 8. THE EFFECT OF TEMPERATURE ON THE RELAXATION OF TITANIUM ALLOYS

(ASM Handbook)

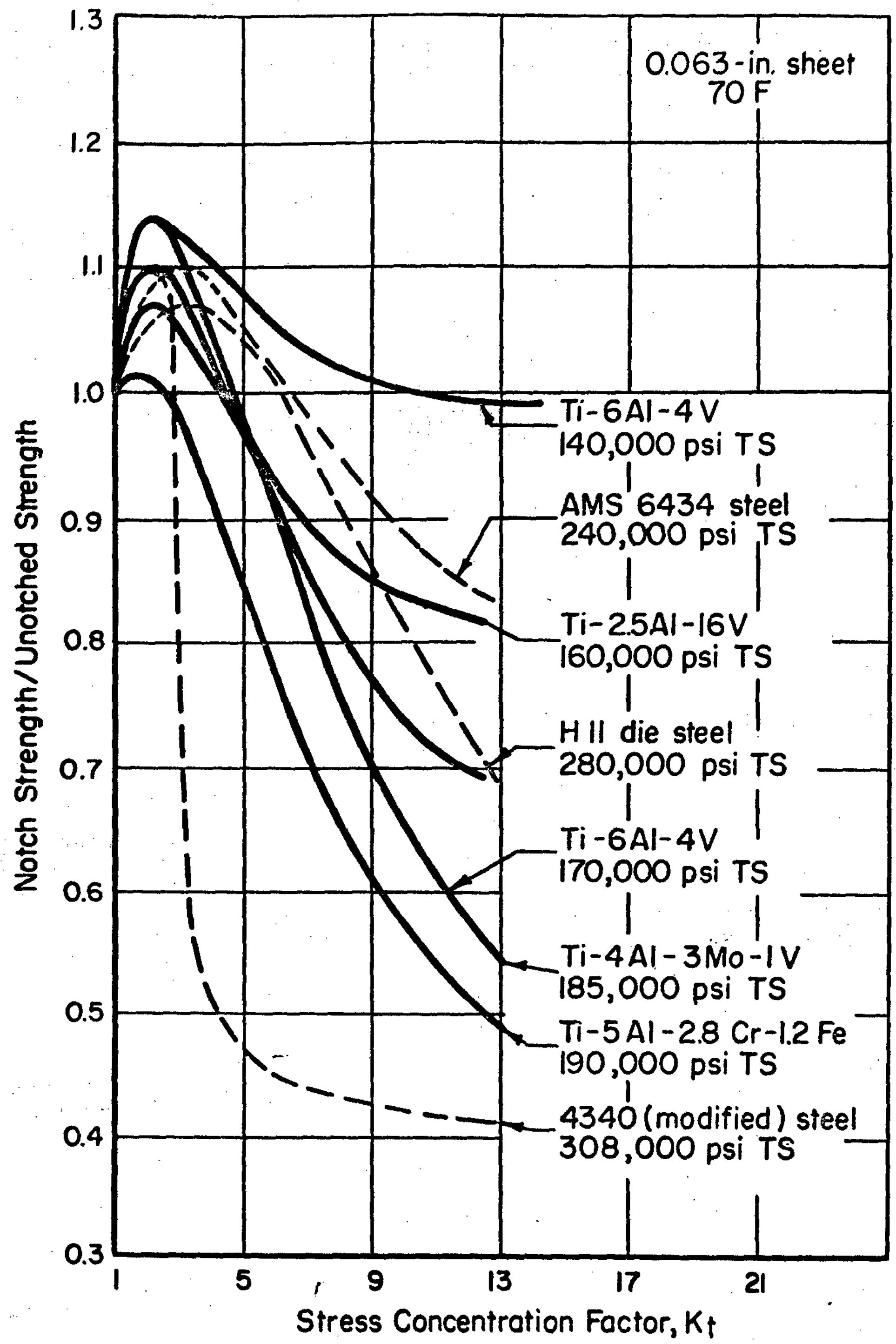

FIGURE 9. EFFECT OF STRESS CONCENTRATION ON THE NOTCH-STRENGTH RATIO OF TITANIUM AND STEEL (0.063-INCH SHEET)

(ASM Handbook)

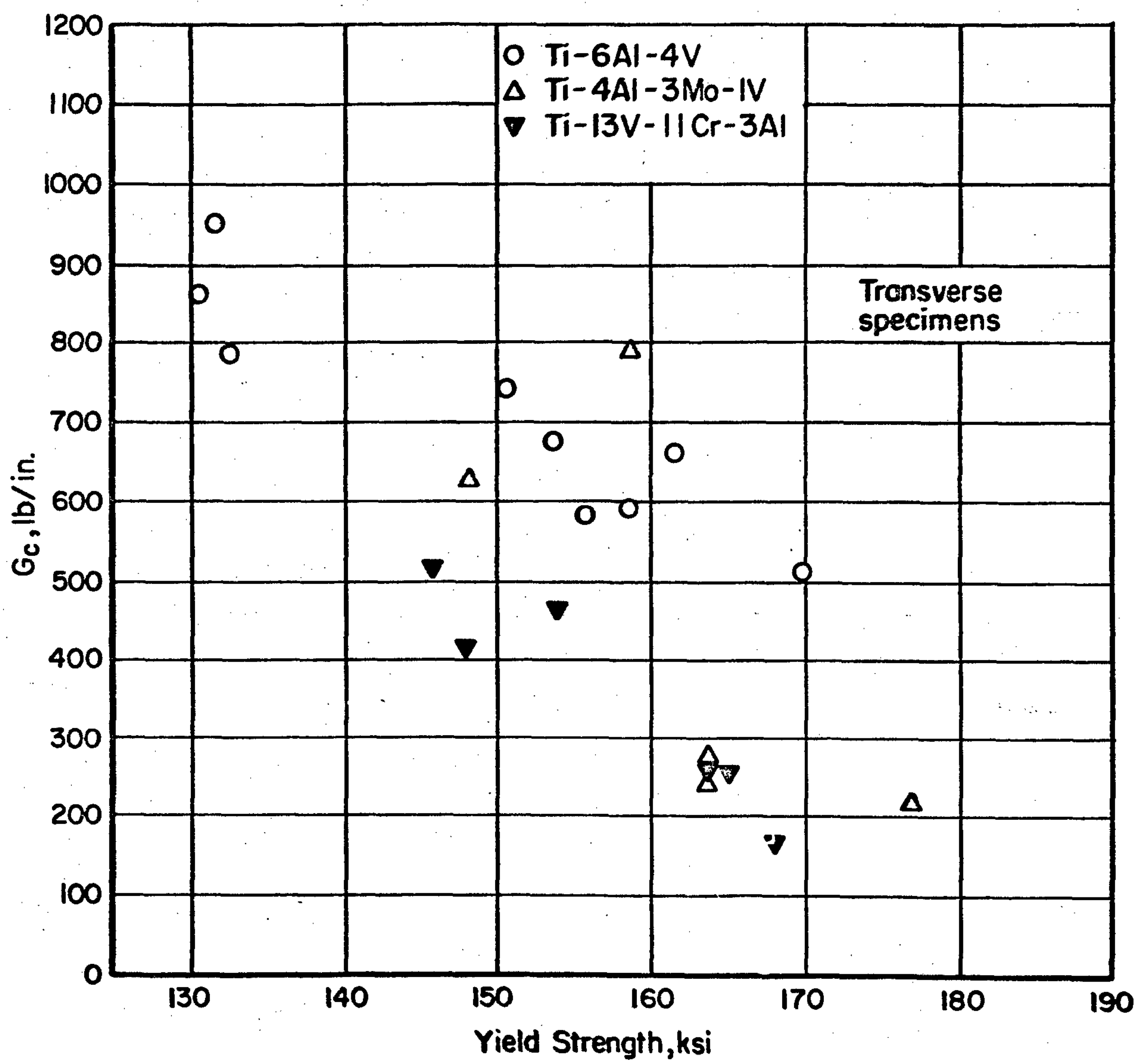

FIGURE 10. RELATIVE VALUES OF G_c VERSUS YIELD STRENGTH FOR Ti-6Al-4V, Ti-4Al-3Mo-1V AND Ti-13V-11Cr-3Al

(Hatch, A. J., "Crack Propagation Characteristics of Three Titanium Alloys", Trans. AIME, 1961.)

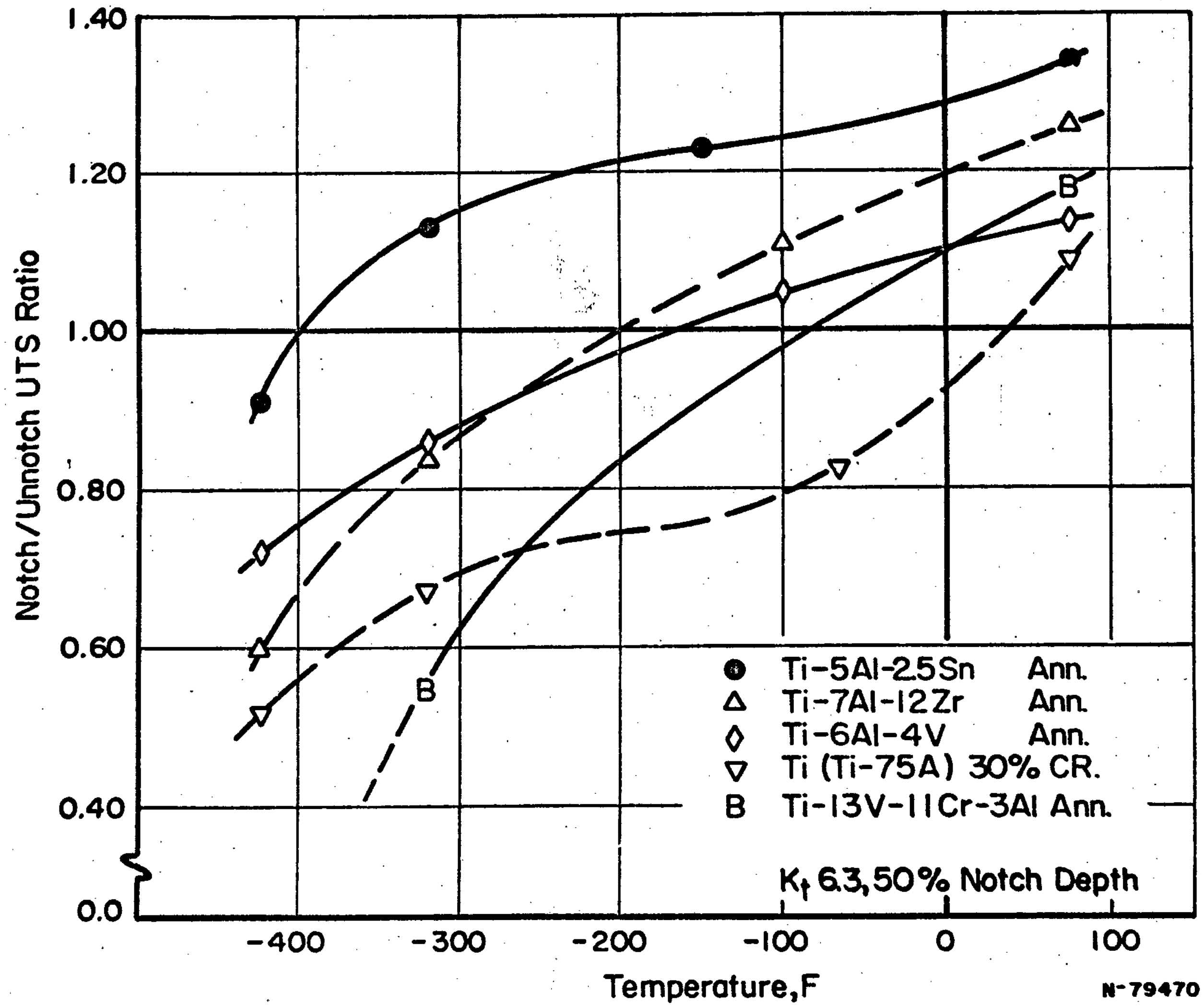

FIGURE 11. NOTCH/UNNOTCH TENSILE-STRENGTH RATIO OF TITANIUM ALLOYS AT CRYOGENIC TEMPERATURES

(Data from Hurlich, Convair Astronautics Division)

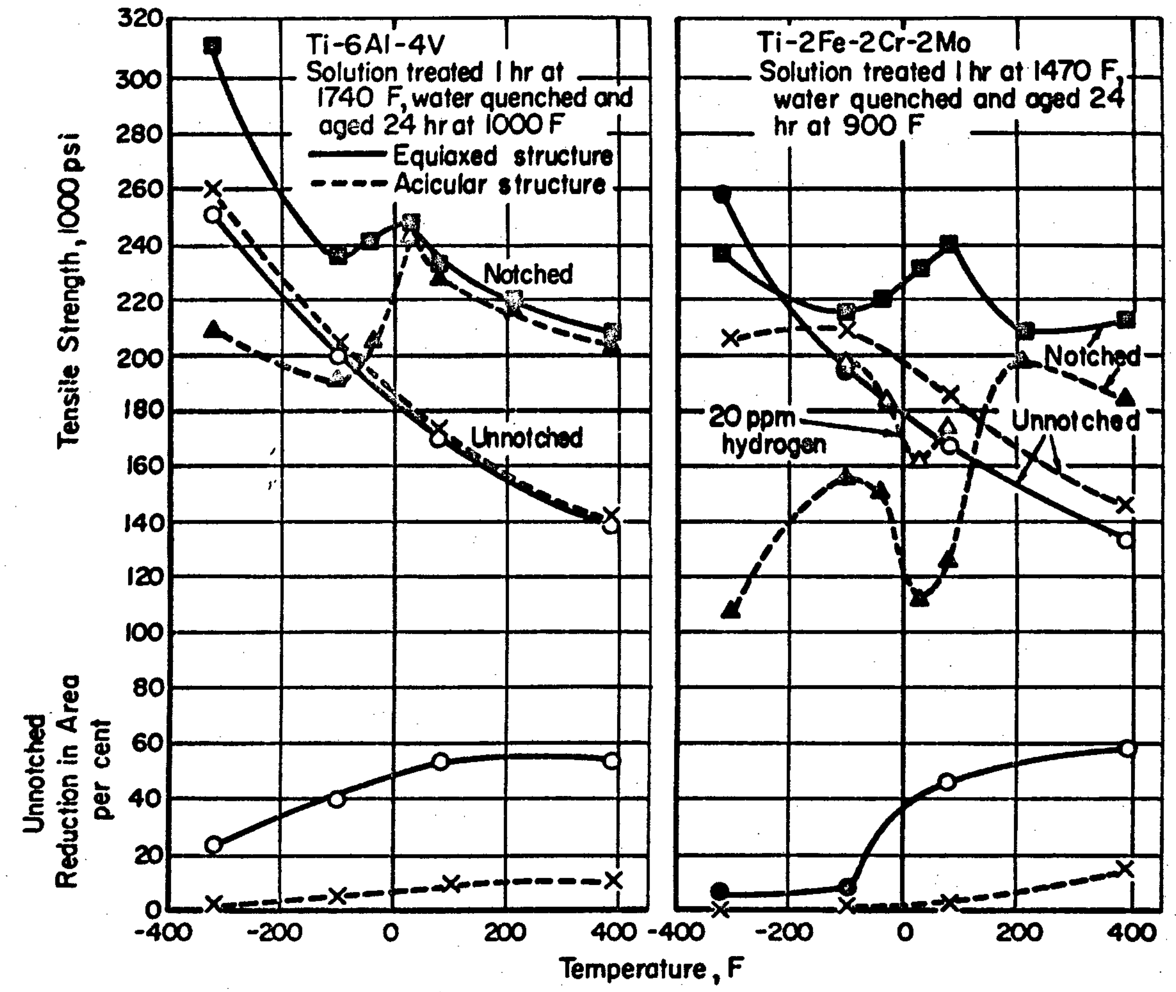

FIGURE 12. EFFECT OF TEMPERATURE ON THE UNNOTCH AND NOTCH TENSILE STRENGTH OF HEAT-TREATED Ti-6Al-4V AND Ti-2Fe-2Cr-2Mo

(Ogden, H. R., et al. "The Notch Sensitivity of Ti-5Al-2.5Sn, Ti-6Al-4V, and Ti-2Fe-2Cr-2Mo Titanium Alloys", Trans. AIME, 1961)

Fatigue

Figure 13 illustrates the fatigue-endurance limit of titanium alloys against tensile strength, compared with quenched and tempered low-alloy steels. For a given strength level, the fatigue limits for titanium alloys fall both above and below the range for steel. If allowance is made for density, the fatigue strengths generally are above those for steels.

Uniformity

Uniformity of properties in a structural material permits designers to increase the allowable stresses. Generally, this is done from estimates of the standard deviation expected from the average properties of the material. In a design to $\pm 1\sigma$, 68 per cent of all values fall within the distribution curve, while a 2σ design allows for 95 per cent reliability. A recent statistical compilation of the consistency of titanium sheet products is illustrated in Table 5. Data from the compilation were taken for production from the titanium-sheet-rolling program and data provided by the producers of aircraft. The sigma values of the strength of titanium-sheet products, both annealed and heat treated, range from 5,000 to 10,000 psi and are generally about 5 per cent of the average strength.

Airframe and Aerospace Applications

The Airframe

Titanium is used in airframes for firewalls, nacalles, skins, frames, longerons, hatch doublers, keels, speed-brake doors, crack arresters, fasteners, forgings, extrusions--in other words, in practically all types of components. Utilization of titanium in airframes in manned aircraft has increased steadily since it was introduced in the early 1950's. For example, McDonnell Aircraft Company used about 30 pounds of titanium in the F3H (0.3 per cent) designed in 1951, 300 pounds in the F101 (2.9 per cent) designed in 1952, and about 800 to 900 pounds in the F4H (7.5 per cent) designed in 1954. This indicates that an aircraft manufacturer making a single class of vehicles designed increasing amounts of titanium into successive models. A second interesting case is the B52 bomber, where the first model, B52A, designed in 1947 and produced in 1953, contained 660 pounds of titanium (0.8 per cent), whereas the B52G, designed in 1955 and produced in 1956, contained about 2000 pounds of titanium (over 2 per cent). Thus, in successive models of a given aircraft, titanium was increasingly used. Other examples of the trend toward increasing use of titanium in the design of airframes includes the F86 - F100 series and the FJ2 - FJ3 - FJ4 - A3J series of North American Aviation, where the percentage utilization of titanium increased from 1 to 7 per cent of the structural weight. The NAA's X-15 rocket ship contains 17.5 per cent titanium in its structure. A 1960 estimate of the utilization of titanium in military airframes over the period 1961 to 1968 forecast an average titanium content of 2 per cent of the structural weight in 1961 and 8 to 9 per cent in 1965 to 1968. Over the same span, titanium utilization by 1965 might go as high as 30 per cent (including missile structures), assuming successful completion of alloy development and product-improvement programs.

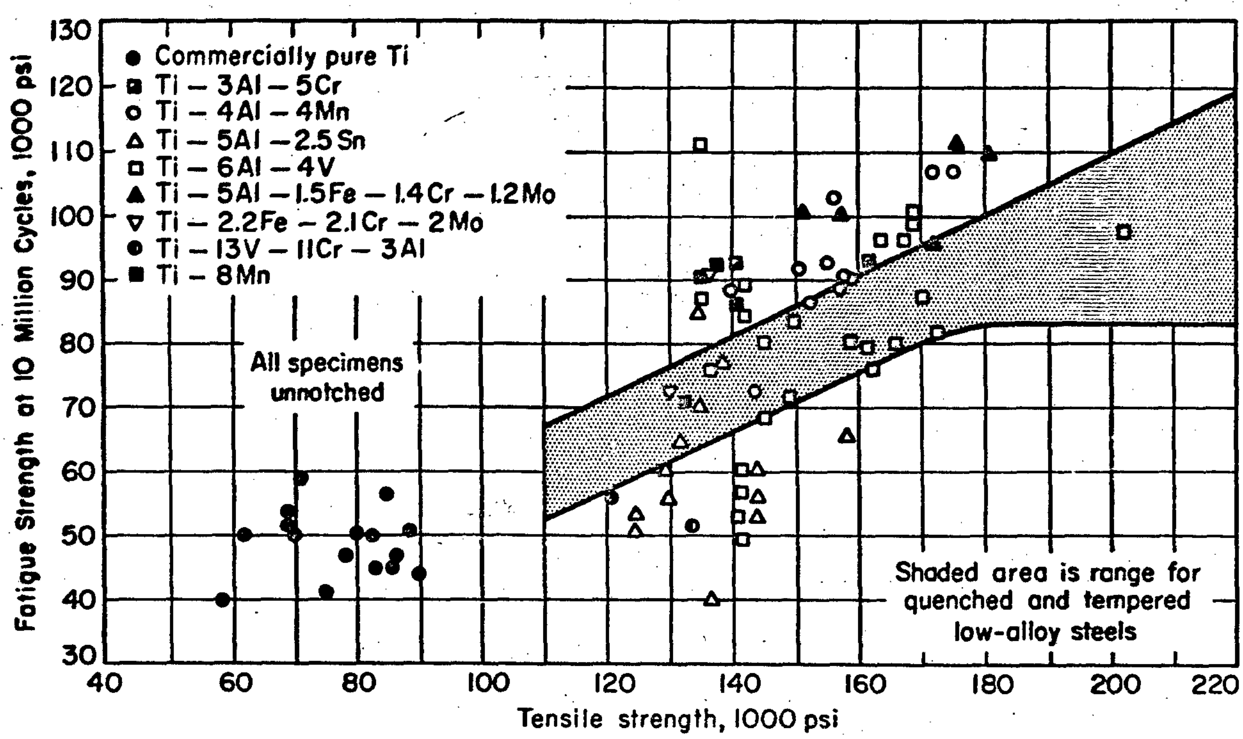

FIGURE 13. FATIGUE DATA FOR TITANIUM, COMPARED WITH QUENCHED AND TEMPERED STEELS

(ASM Handbook)

TABLE 5. STATISTICAL DISTRIBUTION OF TITANIUM ALLOY SHEET TENSILE PROPERTIES[a]

Alloy	Condition	Ultimate Strength, ksi		0.2% Yield Strength, ksi		Elongation, %		Number of Tests
		Average	σ	Average	σ	Average	σ	
5Al-2.5Sn	Annealed	127.5	7.0	120.4	7.4	13.4	2.2	1640
8Mn	Annealed	150.6	8.7	142.9	11.5	18.3	4.0	113
5Al-2.8Cr-1.2Fe	Solution Treated and Aged	187.1	14.9	163.6	8.6	7.8	2.4	375
4Al-3Mo-1V	Solution Treated and Aged	199.6	8.5	173.1	12.2	5.5	1.6	575
4Al-3Mo-1V	Solution Treated and Aged (L)	200.2	7.1	172.4	9.3	5.5	1.3	1420
4Al-3Mo-1V	Solution Treated and Aged (T)	201.0	8.6	174.5	9.3	5.9	1.5	1430
6Al-4V	Annealed	135.5	6.7	130.6	7.2	12.8	2.4	2600
6Al-4V	Solution Treated and Aged	175.3	7.7	163.8	11.5	6.4	1.9	589
Ti-16V-2.5Al	Solution Treated and Aged (L)	176.3	7.5	162.2	7.5	5.7	1.4	750
Ti-16V-2.5Al	Solution Treated and Aged (T)	180.0	8.3	167.6	8.6	5.1	1.3	750

(a) From DMIC Memorandum 87, "A Statistical Summary of Mechanical Property Data for Titanium Alloys", W. S. Lyman, February 14, 1961.

Nacelles and firewalls are examples of nonstructural applications of titanium. Firewalls generally are made of unalloyed titanium and are used in areas between the airframe structure and the jet engines. Unalloyed titanium also is used in nacelles. The DC-7 aircraft of Douglas Aircraft Company had 450 pounds of titanium in nacelles per aircraft in the early version, and 800 pounds in the DC-7C. The DC-8 jet aircraft also has considerable titanium in shrouding, pylon, and access panels surrounding the engines. Figure 14 shows the titanium pylon apron and access panels, while Figure 15 illustrates the operation of the access panels.

The basic structure of the Mercury space capsule was sheet-stringer titanium construction. A two-layered, truncated cone of unalloyed titanium was spot welded to an unalloyed titanium frame, as shown in Figure 16. The adapter section between the capsule and the booster had a Ti-5Al-2.5Sn alloy skin riveted to a titanium housing. The capsule proper was made of two concentric cones, with the external cone of beaded 0.010-inch titanium seam welded to an interior cone of 0.010-inch titanium, as shown in Figure 17. Air tightness is essential in the seam and butt welds. Outside the titanium structure, shingles of beryllium and René 41 were used for heat shielding. The blunt-end heat shield also was made of beryllium.

The aft fuselage of jet airplanes is heated by engine radiation. Figure 18 shows the aft fuselage of the F100, a typical structural application for alloyed titanium. The sheet-stringer construction is illustrated in Figure 19. The F100 had about 600 pounds of titanium, including 350 pounds of alloy sheet (Ti-8Mn), 230 pounds of unalloyed sheet, and a few pounds of forgings and fittings. Longerons, frames, and exterior skins were made of Ti-8Mn alloy, while unalloyed titanium was used for shrouds, ducting, and the exterior skins at the extreme aft end.

The B70 Valkyrie supersonic prototype bomber has been designed with brazed steel honeycomb sandwich structure in hot, load-carrying areas, and about 7.5 per cent of single-skin riveted titanium sheet-stringer construction for fuselage and other sections. Ti-6Al-4V alloy sheet is to be used where welding is required, and Ti-4Al-3Mo-1V is to be used in parts requiring maximum formability. The substructure is to be made of Ti-6Al-4V and Ti-7Al-4Mo bar, forgings, and extrusions. The titanium alloys will be heat treated to 160 to 190-ksi tensile strength.

Many supersonic transports, of Mach 3 cruise capability, are being conceived with construction basically of the B70-type: steel honeycomb and titanium sheet-stringer construction. The high cost of brazed honeycomb, either steel or titanium, deters extensive usage, and sheet-stringer construction is used to a greater extent than would be desirable on purely technical considerations. Promising development work on brazed titanium honeycomb has been done, using commercially pure core and alloy cover sheets. These develop about the same strength as steel but are 30 per cent lighter. A new development which may bring the cost of titanium sandwich panels within reach is the so-called roll-welded sandwich process developed by Battelle for Douglas Aircraft Company. Titanium cover sheets are pressure welded by hot rolling to a corrugated core, the space between the corrugations being filled with a metallic matrix which is subsequently leached. The roll-welded panels may be formed before leaching. Costs for producing corrugated-core-sandwich

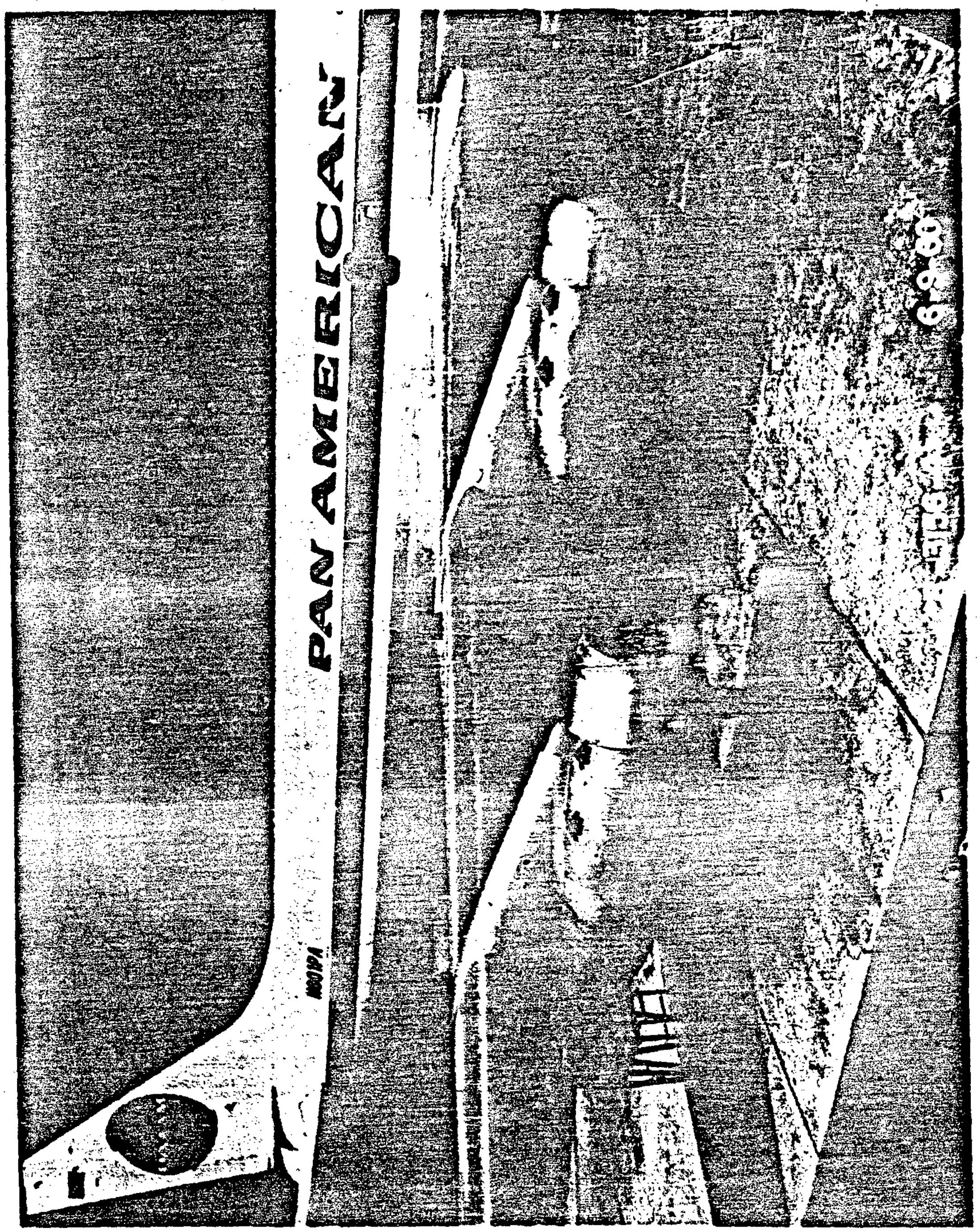

FIGURE 14. TITANIUM PYLON APRON AND ACCESS PANELS IN THE DC-8

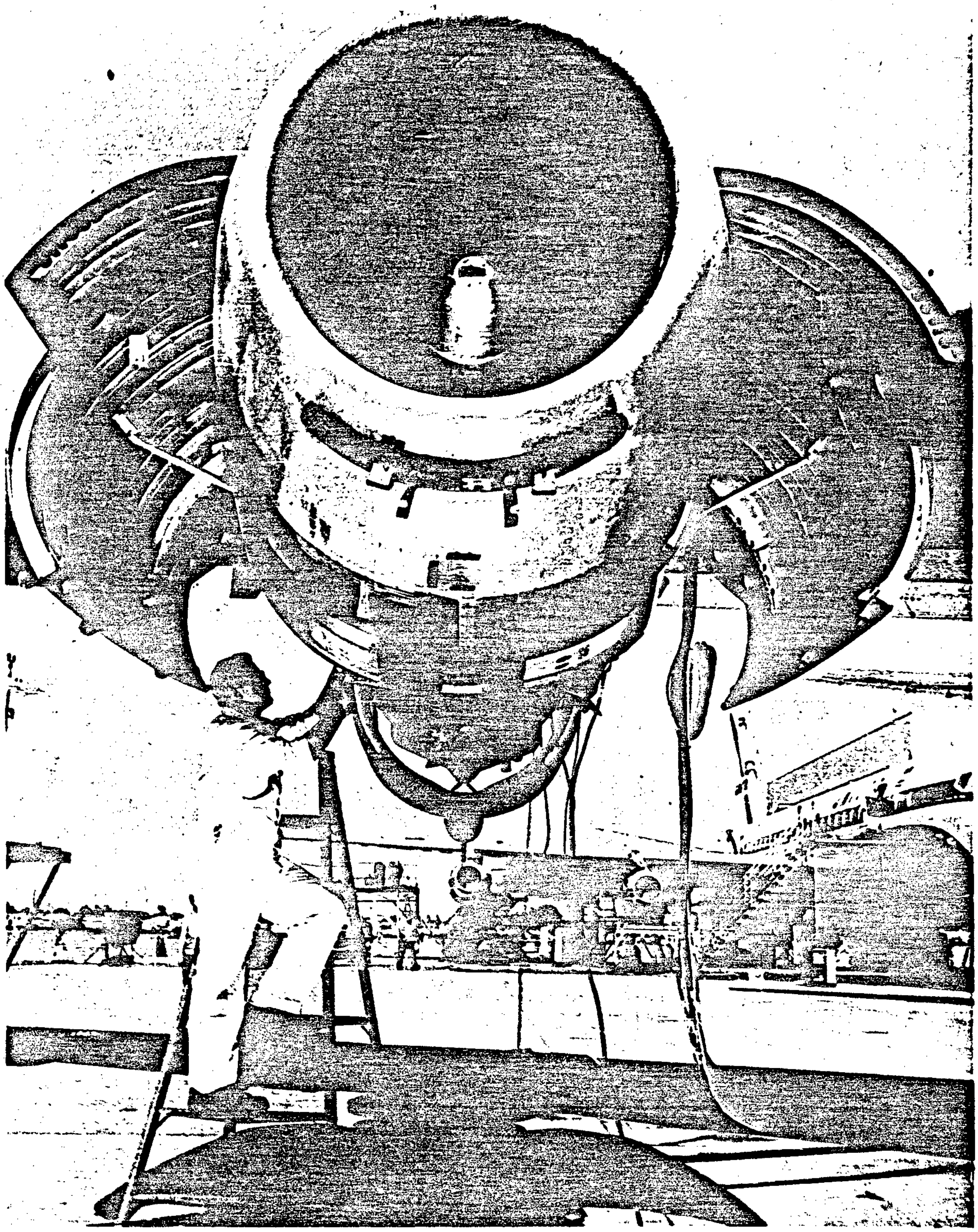

FIGURE 15. OPERATION OF TITANIUM ACCESS PANELS IN THE DC-8

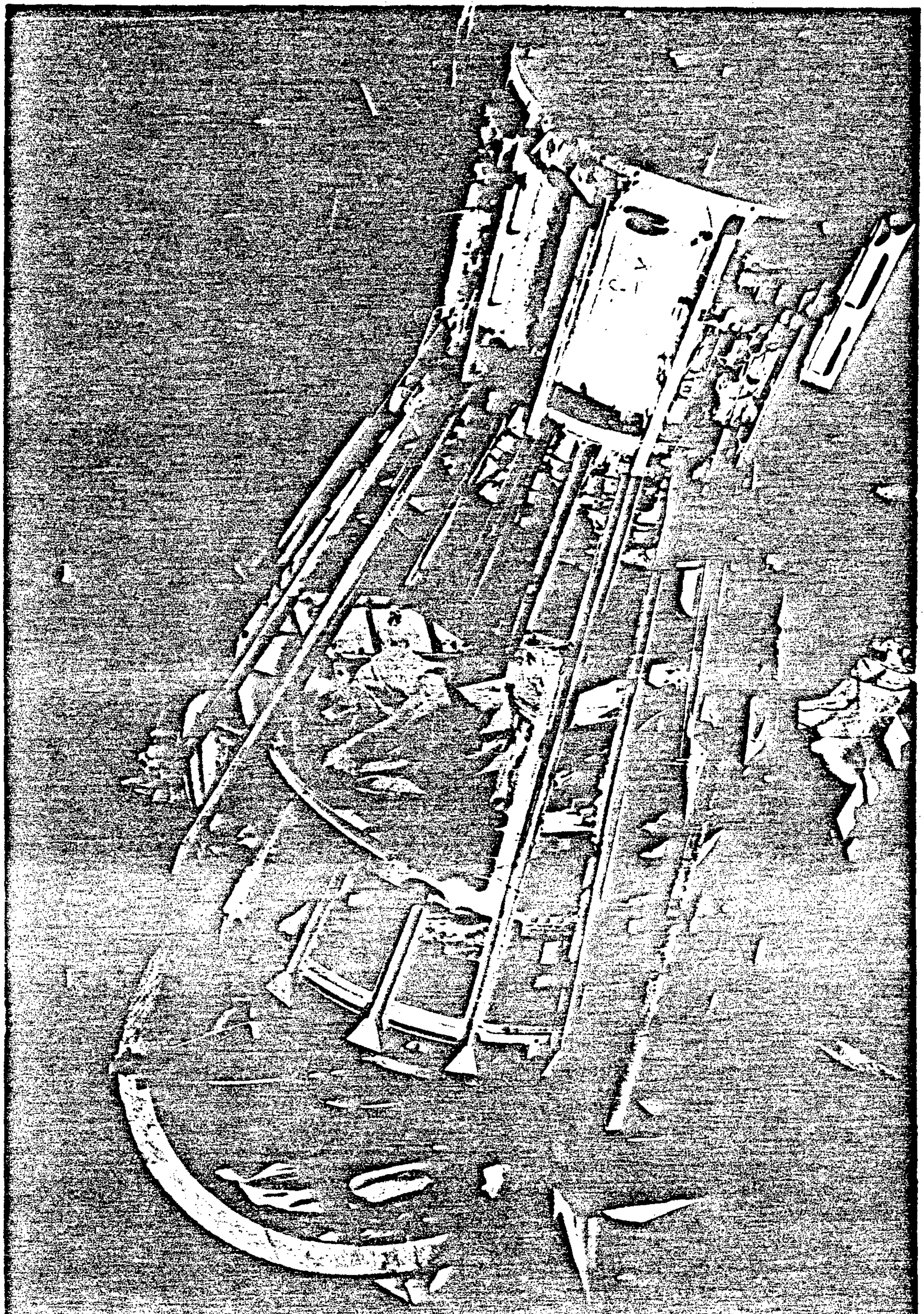

FIGURE 16. TITANIUM FRAME IN PROJECT MERCURY SPACE CAPSULE

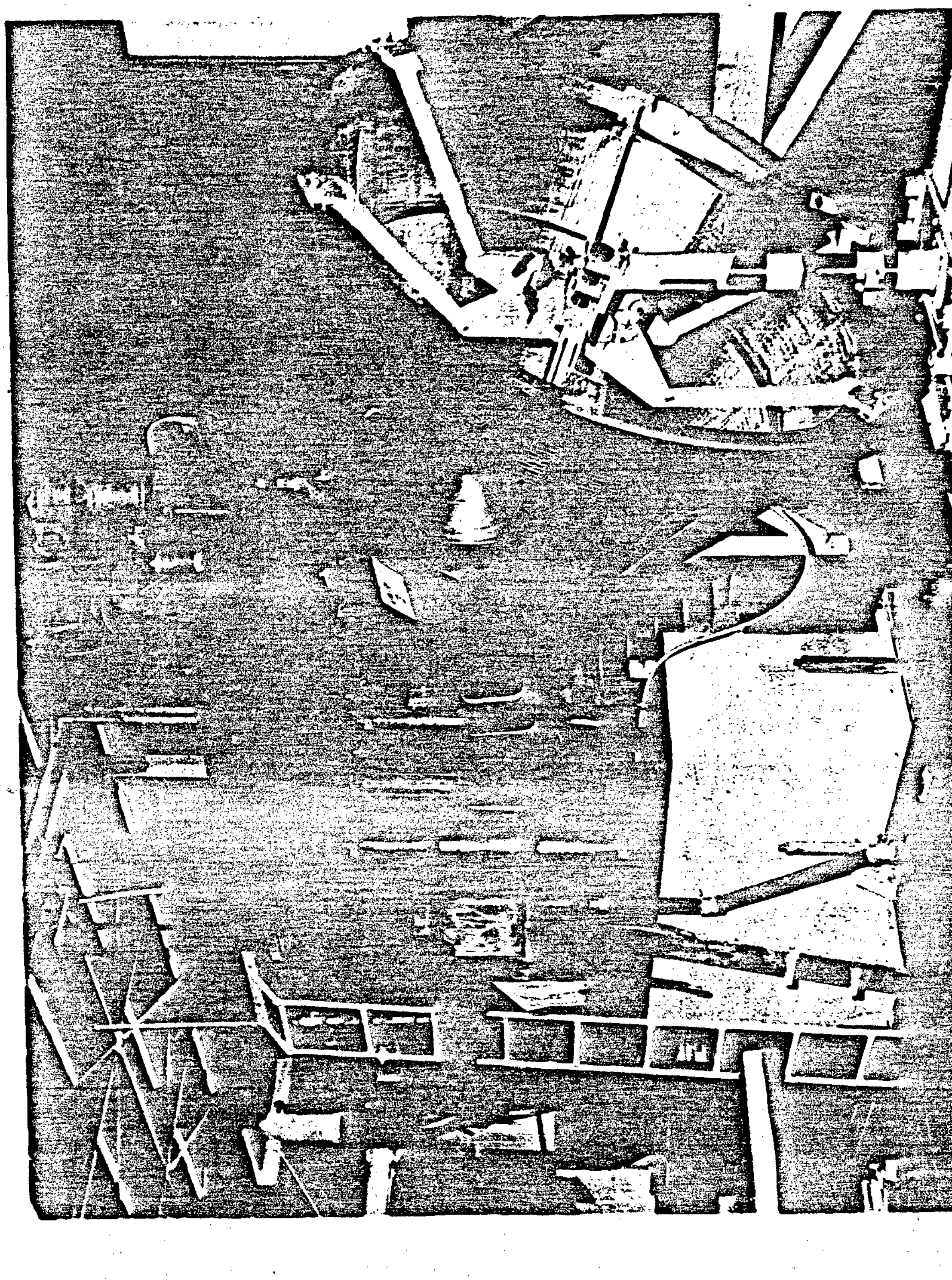

FIGURE 17. SEAM WELDING BEADED TITANIUM CONE TO INTERIOR CONE OF MERCURY CAPSULE

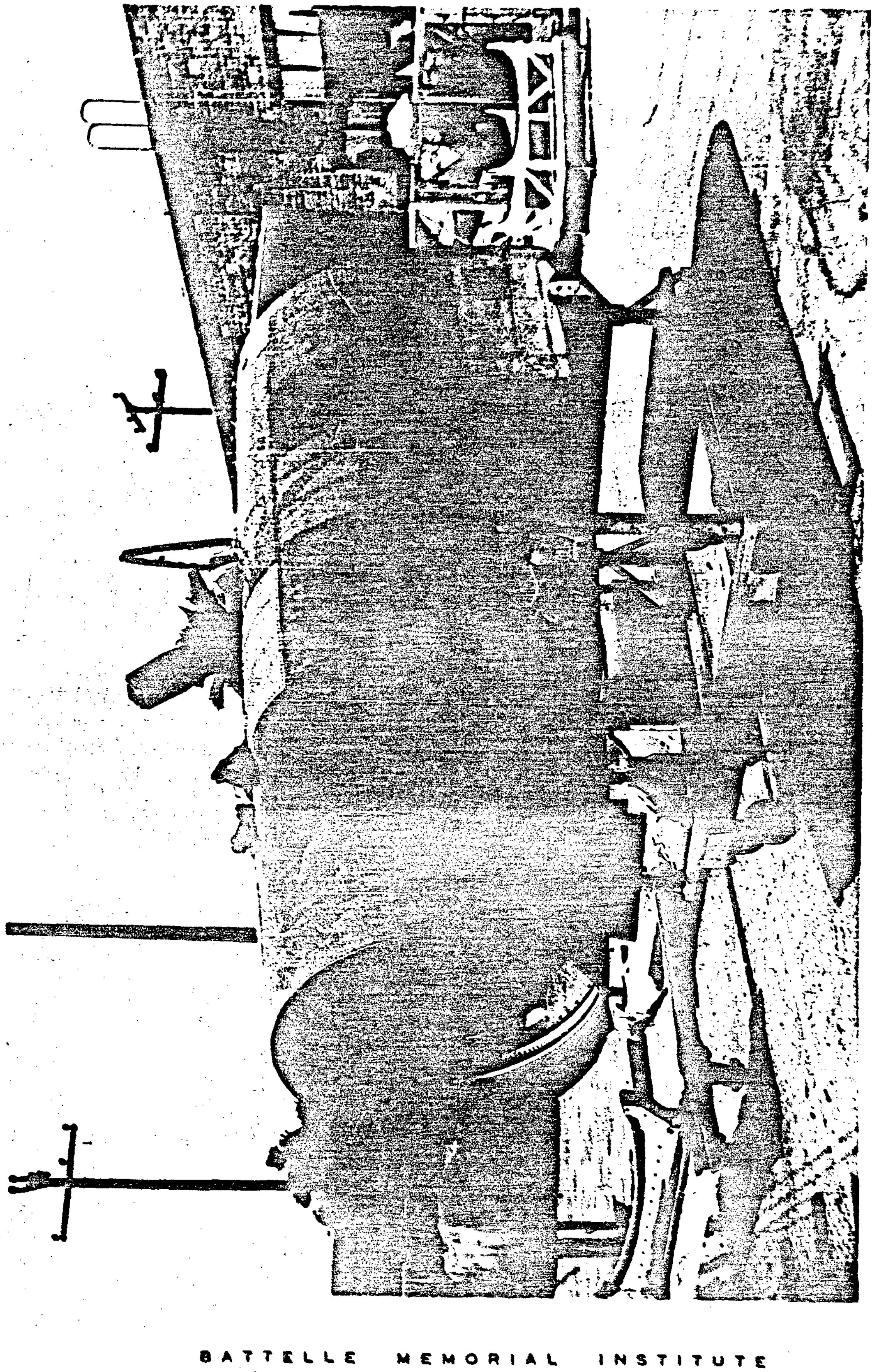

FIGURE 18. TITANIUM-ALLOY AFT FUSELAGE OF F100

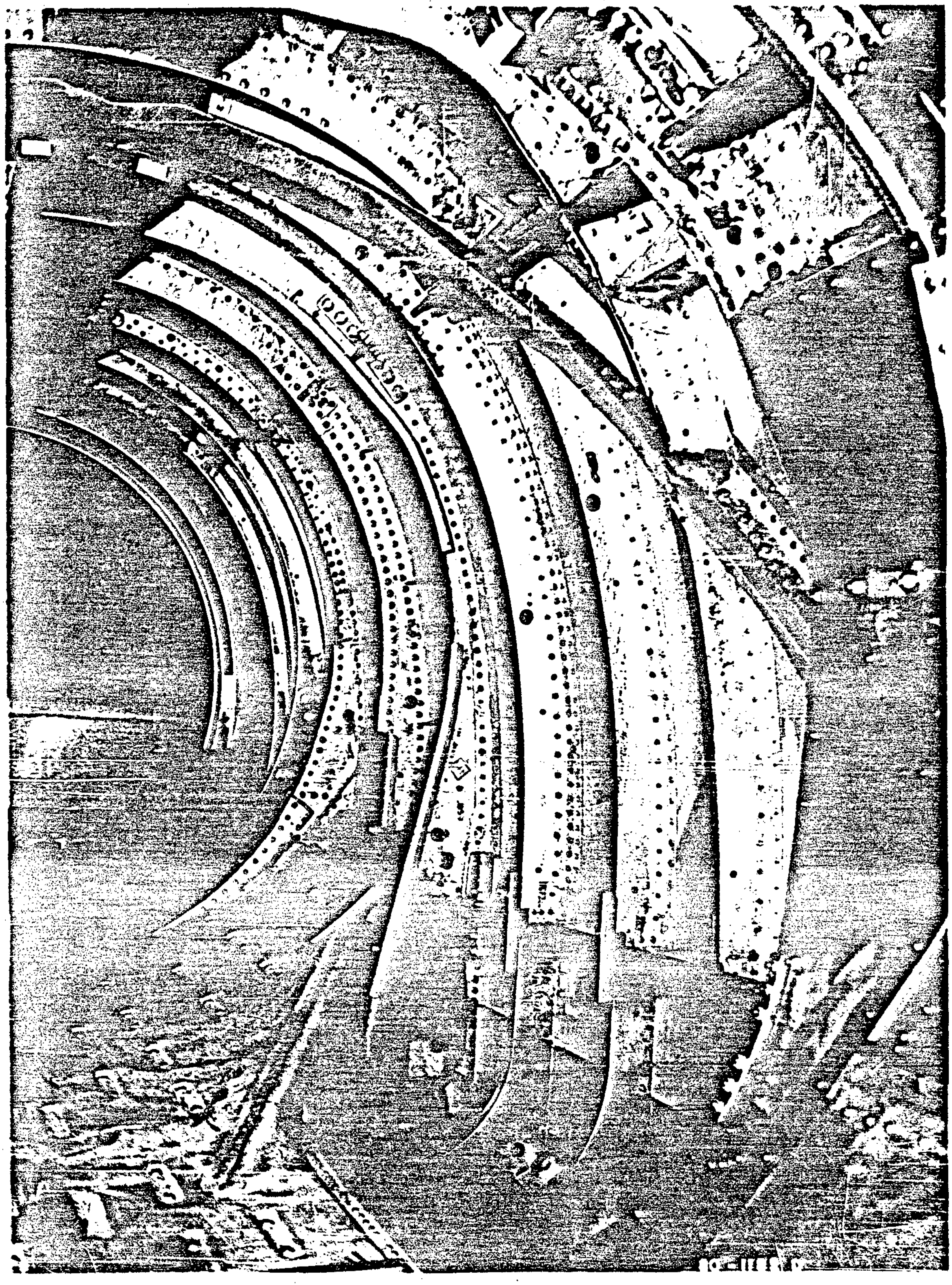

FIGURE 19. SHEET-STRINGER CONSTRUCTION USED IN F100 AFT FUSELAGE

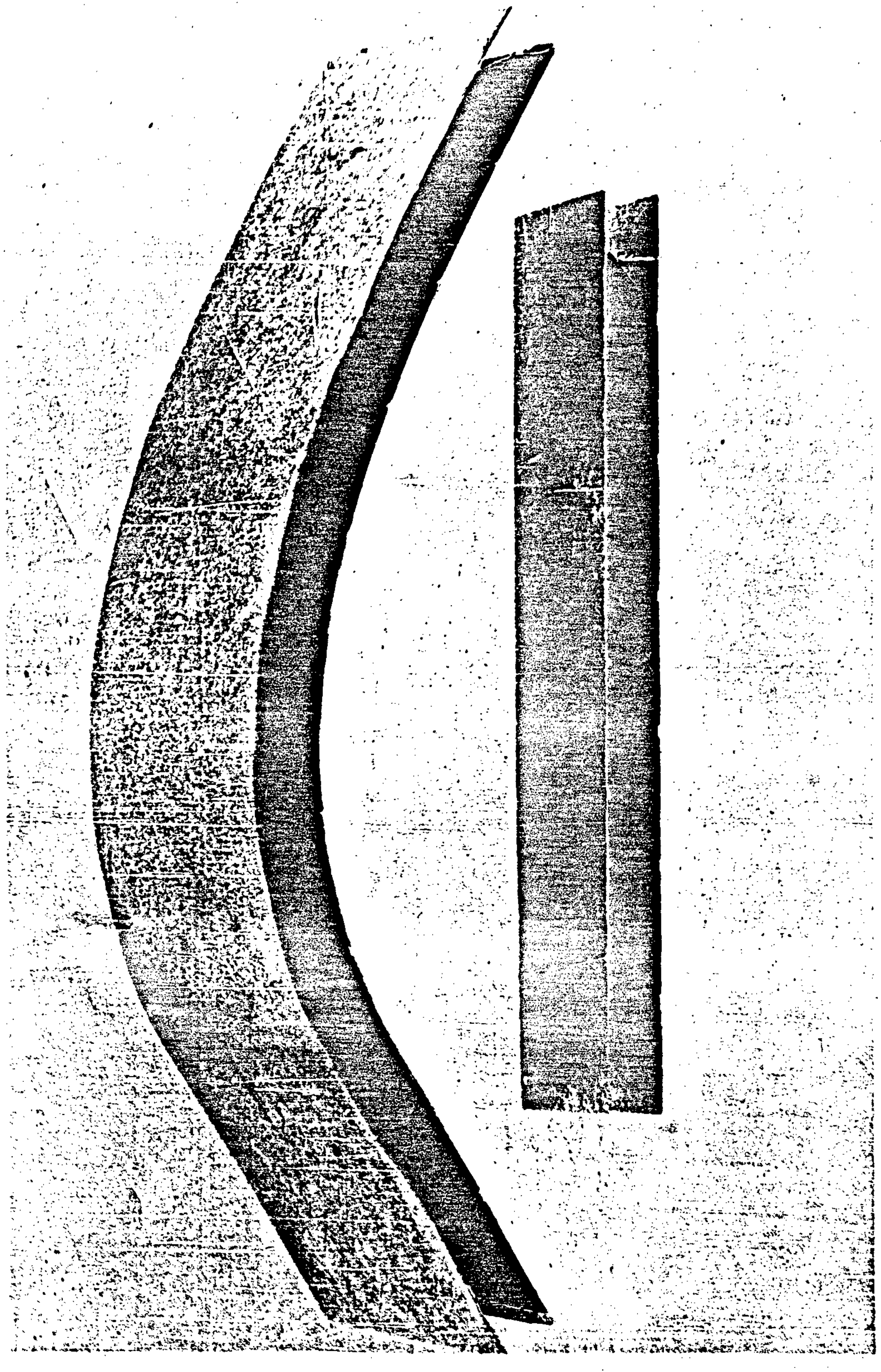

FIGURE 20. ROLL-WELDED TITANIUM SANDWICH PANELS
AFTER LEACHING OF CORE

cylinders have been estimated at less than half that of alternative processes. Figure 20 shows formed and flat sections of titanium sandwich after leaching.

An example of using titanium because of its good notch toughness are the rip stoppers in the DC-8. Rip stoppers of Ti-6Al-4V sheet at frames and cutouts are used to the extent of 330 pounds. Figure 21 illustrates the attachment of Ti-6Al-4V rip stoppers to the frames of the forward section. Figure 22 illustrates the interior after installation of the skins. Figure 23 shows a Ti-6Al-4V door-jamb doubler.

Aircraft forgings of large section size, which are stiffness critical, comprise an area in the airframe where titanium competes successfully with aluminum alloys at room temperature. Typical titanium forgings include engine mounts, wing attachments, bomb racks, and slat tracks. Titanium alloy forgings are generally made of Ti-6Al-4V, Ti-4Al-4Mn, Ti-7Al-4Mo, and Ti-155A, and are heat treated to about 160-ksi yield strength and 180-ksi ultimate strength. A heat-treated Ti-6Al-4V rib forging for the A3J, shown in Figure 24, is 52 inches long and weighs approximately 50 pounds. As solution treated 1 hour at 1700 F, water quenched, and aged 4 hours at 1000 F, it had the following average tensile properties:

Direction	Ultimate Tensile Strength, ksi	Offset Yield Strength, 0.2% ksi	Elongation, %	Reduction of Area, %
Longitudinal	168	152	16	36
Long Transverse	170	154	16	39
Short Transverse	157	142	16	38

The transverse ductility is seen to be excellent. One of the largest titanium forgings produced is the horizontal stabilizer rib for the A3J, weighing 170 pounds, shown in Figure 25. Titanium forgings could well be used in landing gear, where 150-ksi titanium forgings would be equivalent to steel at 250 to 280 ksi. Titanium alloys also are being developed for landing wheels, as indicated by Figure 26. Anticipated advantages of titanium wheels are primarily high strength-weight ratios, good fatigue resistance, and elevated-temperature capabilities.

Titanium fasteners are used extensively in the B52G and other heavy jet aircraft. However, the cost of these fasteners has remained high despite reductions in base-metal cost and improved manufacturing practice. It is necessary to roll the threads in titanium fasteners and to pretorque those used at elevated temperature to avoid fatigue failures.

The Jet Engine

Jet engines have provided the backbone application for the titanium industry. The J57 engine of Pratt & Whitney Aircraft utilizes 7 to 15 per cent titanium on a dry-weight basis. General Electric Company

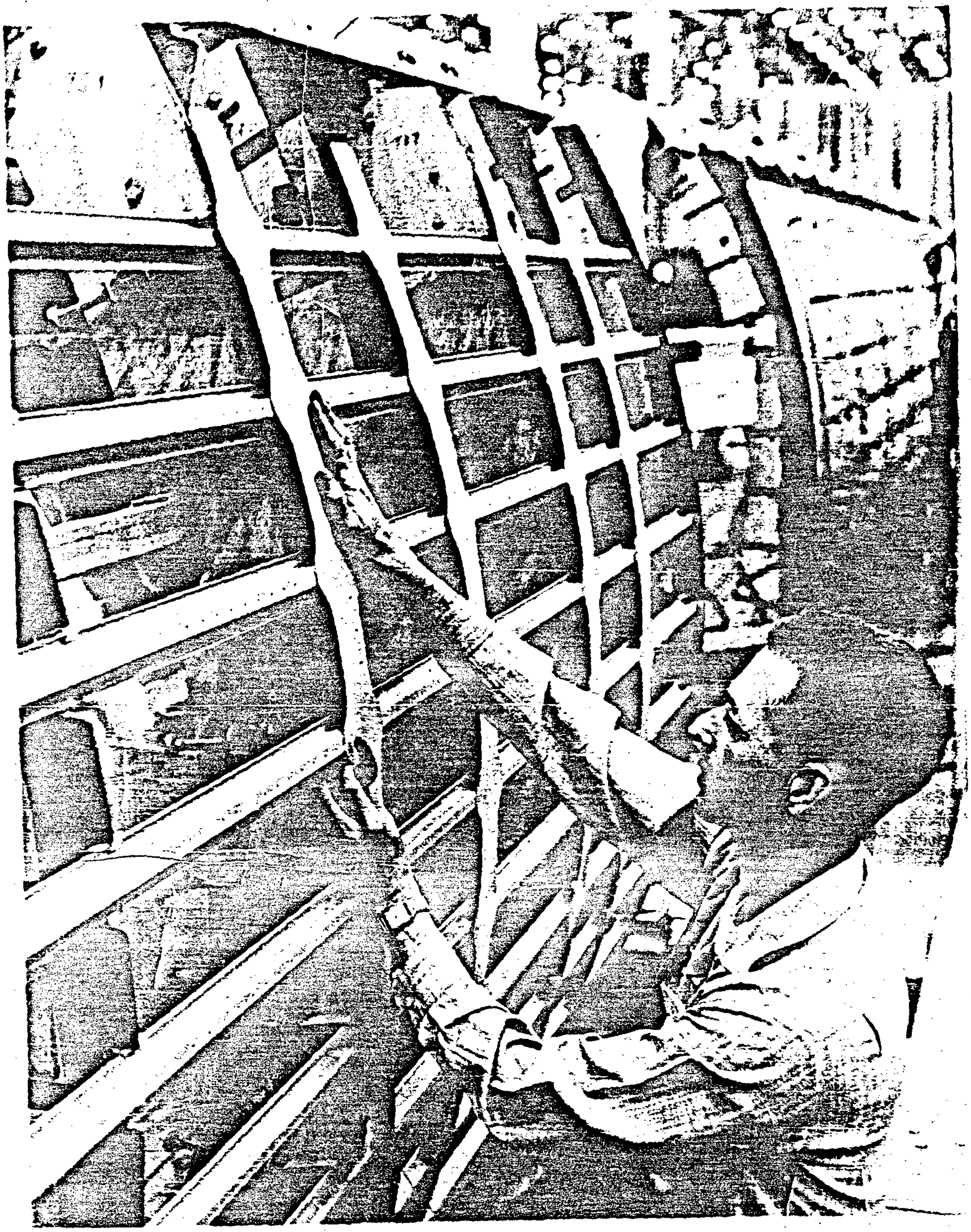

FIGURE 21. TITANIUM-ALLOY RIP STOPPERS BEING INSTALLED IN DC-8

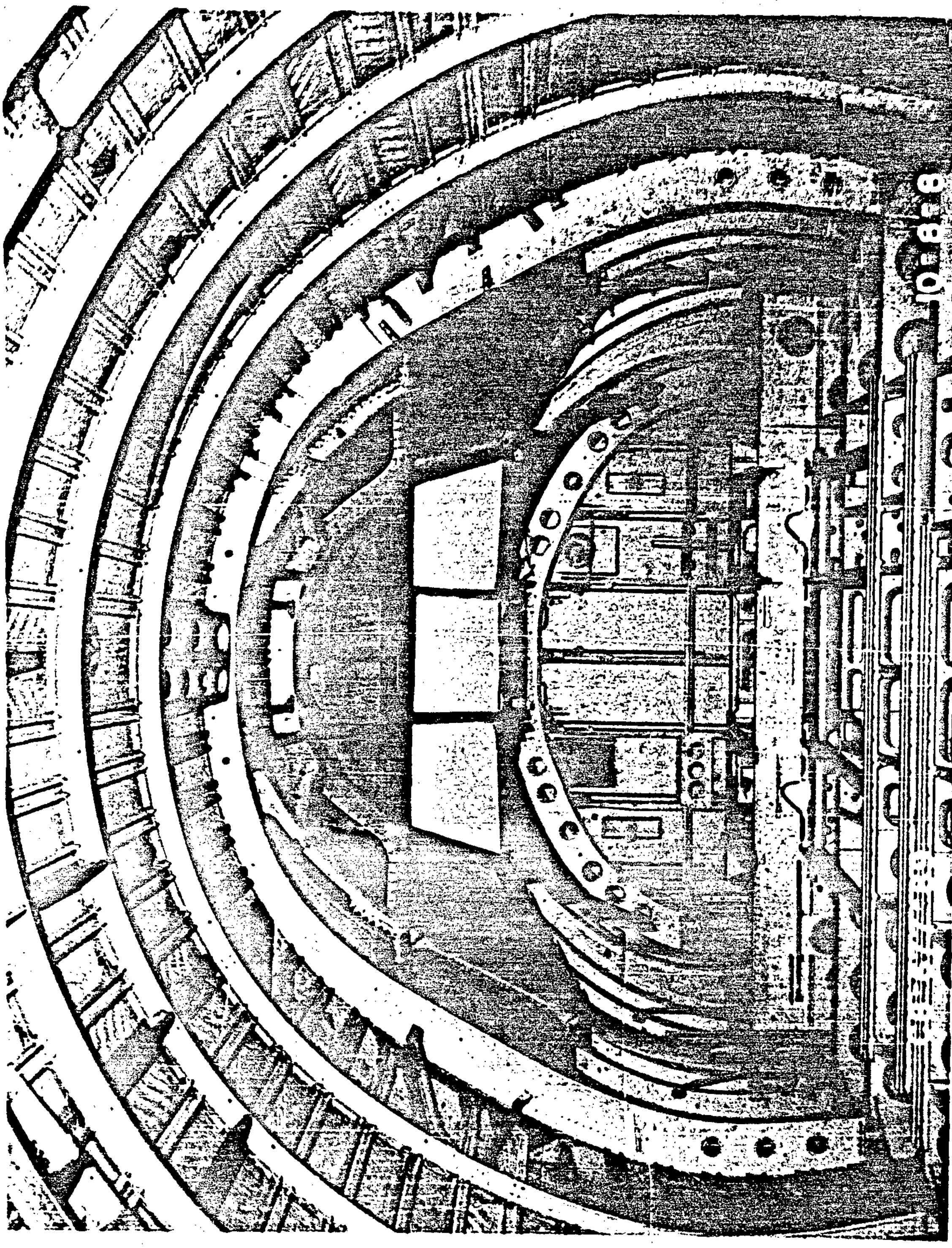

FIGURE 22. INTERIOR VIEW SHOWING TITANIUM-ALLOY RIP STOPPERS IN DC-8

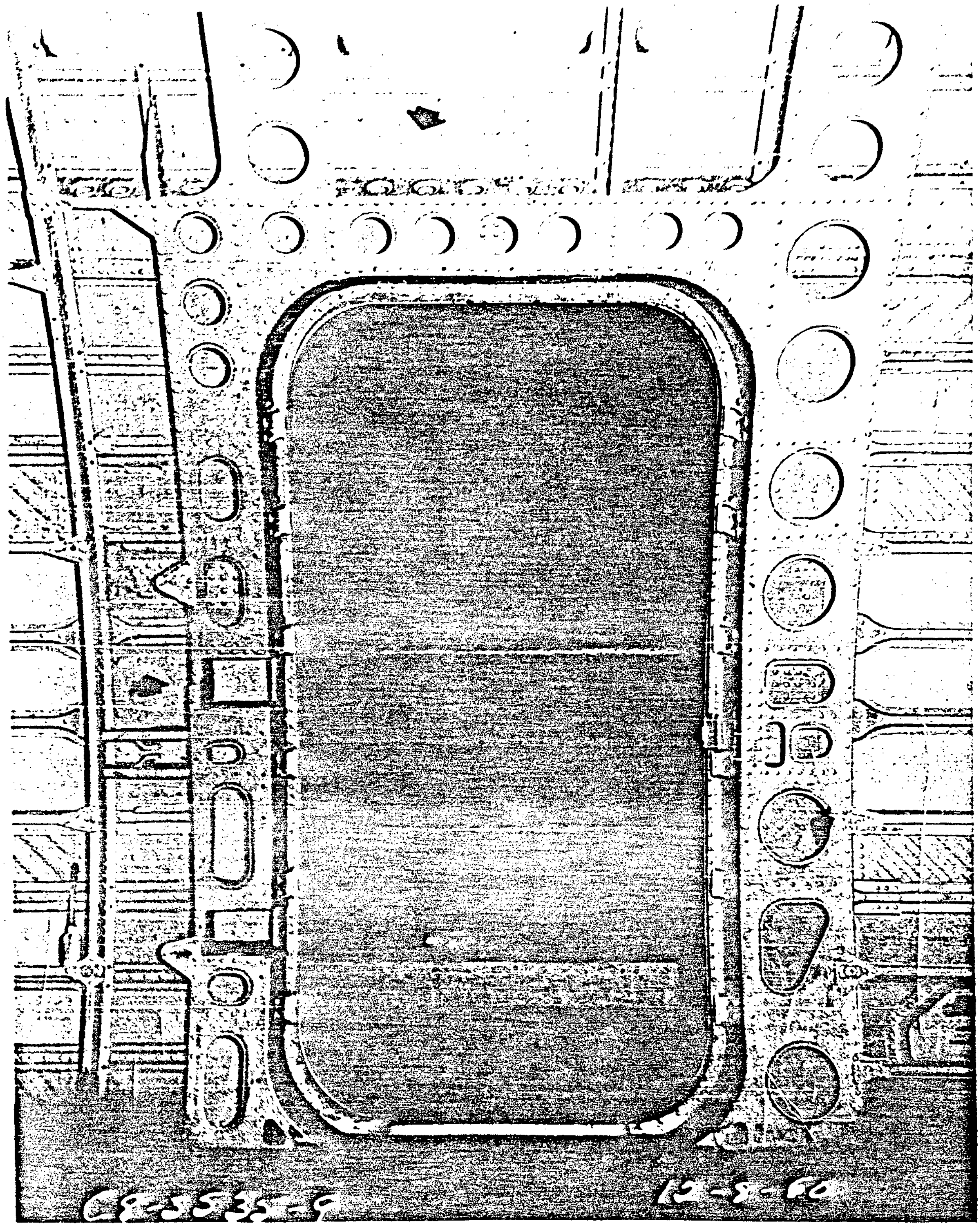

FIGURE 23. TITANIUM-ALLOY DOOR-JAMB DOUBLER IN DC-8

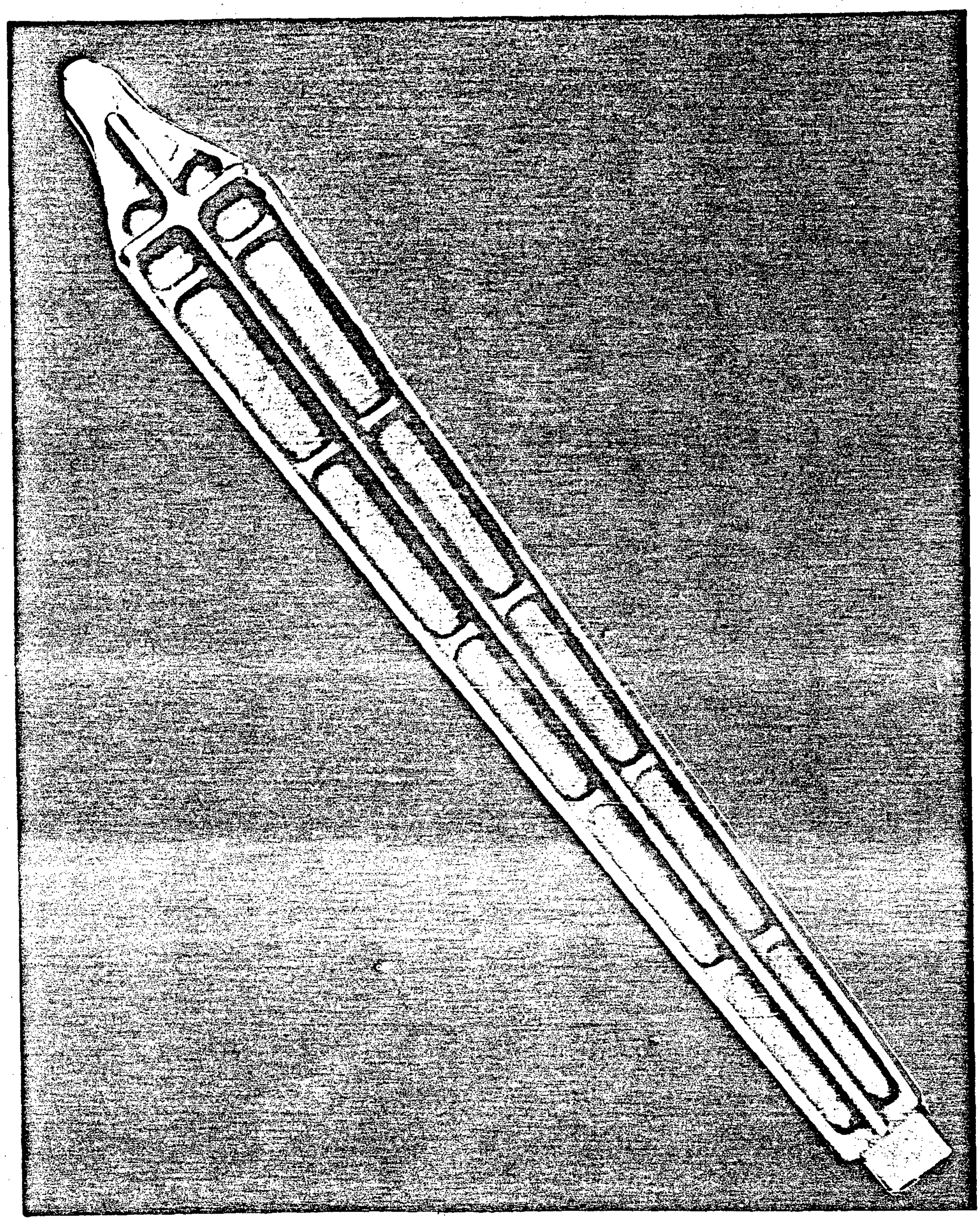

FIGURE 24. HEAT-TREATED TITANIUM-ALLOY
RIB FORGING FOR A3J

FIGURE 25. LARGEST TITANIUM FORGING PRODUCED THUS FAR, 170-POUND HORIZONTAL-STABILIZER RIB FORGING FOR THE A3J

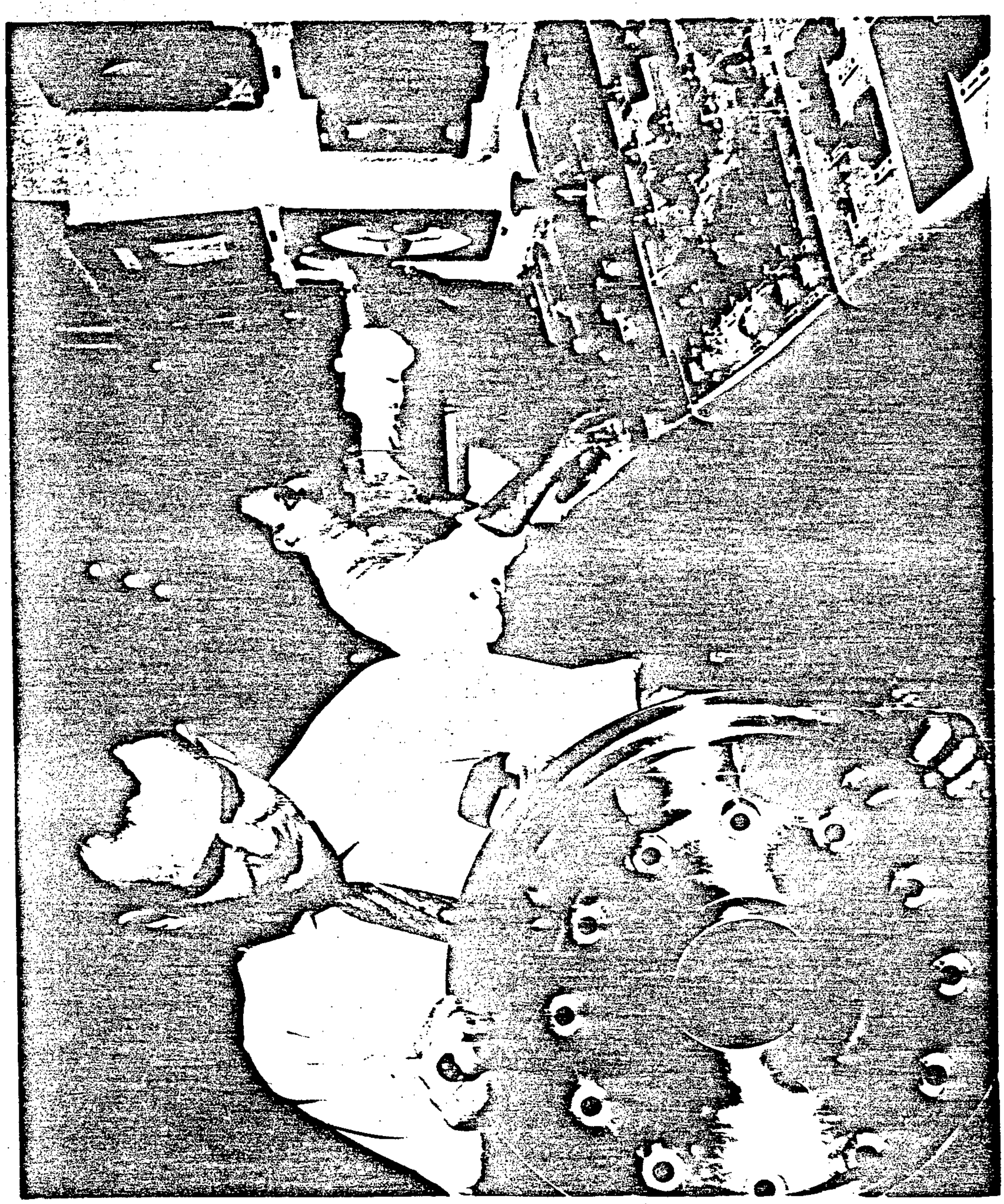

FIGURE 26. TITANIUM-ALLOY LANDING WHEEL DEVELOPED BY GOODYEAR

utilized 6 per cent titanium in the J73 in 1956; dropped titanium completely in the original J79, but, in later versions, incorporated 2 per cent in the J79-8; and are using 4 per cent in the J93-3 engine scheduled to power the B70.

The first Pratt & Whitney J57 engine containing titanium was shipped in 1954. Since that time, several thousand titanium J57 engines have gone into service in B52 bombers, KC-135 tankers, and several different fighter aircraft. Although some nonafterburning engines used for B52 aircraft contained no titanium, the majority have contained titanium varying from 7 to 15 per cent, on a dry-weight basis, depending upon the engine model and its application. For the most part, titanium in J57 engines has been used in the inlet case made of commercially pure titanium, the low-compressor case, also of commercially pure titanium, and in the low-compressor rotor made up of 6Al-4V alloy blades, disks, and disk spacers.

The relatively rapid development of the titanium industry in the United States stemmed primarily from applications in the J57 engine program, which has for over 5 years taken more than 50 per cent of the total United States output of titanium. Melting, sheet rolling, and forging practices used today were initiated under the J57 program. The application of titanium to the latest generation of commercial engines, the turbofans, is a result of the technological advances and price reductions effected under the major military program.

In commercial aircraft, the Pratt & Whitney engines in Boeing 707s 707-120s, 720s, and Douglas DC-8s, made virtually no use of titanium until just recently. Potential weight saving via application of titanium to the JT3A and JT3C engines used for these aircraft could not quite be rationalized with the higher cost. However, with the JT3D turbofan engine (Figure 27) recently introduced into airlines operation, titanium has finally come into its own as a major factor in weight saving and as a contributor to power and efficiency.

The Pratt & Whitney JT3D turbofan engine may be defined as a turbine engine with a ducted, secondary airstream accelerated by a two-stage fan located forward of and integrally with the low compressor. Ducting the fan exhaust overboard, instead of through the combustion chamber, enables the turbofan to produce thrust at a lower cost in fuel consumption. The velocity of air discharged directly from the fan is low because it has not been heated by combustion. Thus, the turbofan's average discharge velocity is substantially reduced and this, coupled with the fact that a much larger mass of air is discharged, results in more thrust and the consumption of less fuel. The greater thrust also enables turbofan-powered aircraft to operate from shorter runways. The JT3D-1 provides the following advantages over the current JT3C-7 engine:

13% lower cruise TSFC
42% more static TO thrust
23% more climb thrust at sea level
16% more cruise thrust
18% lower specific weight.

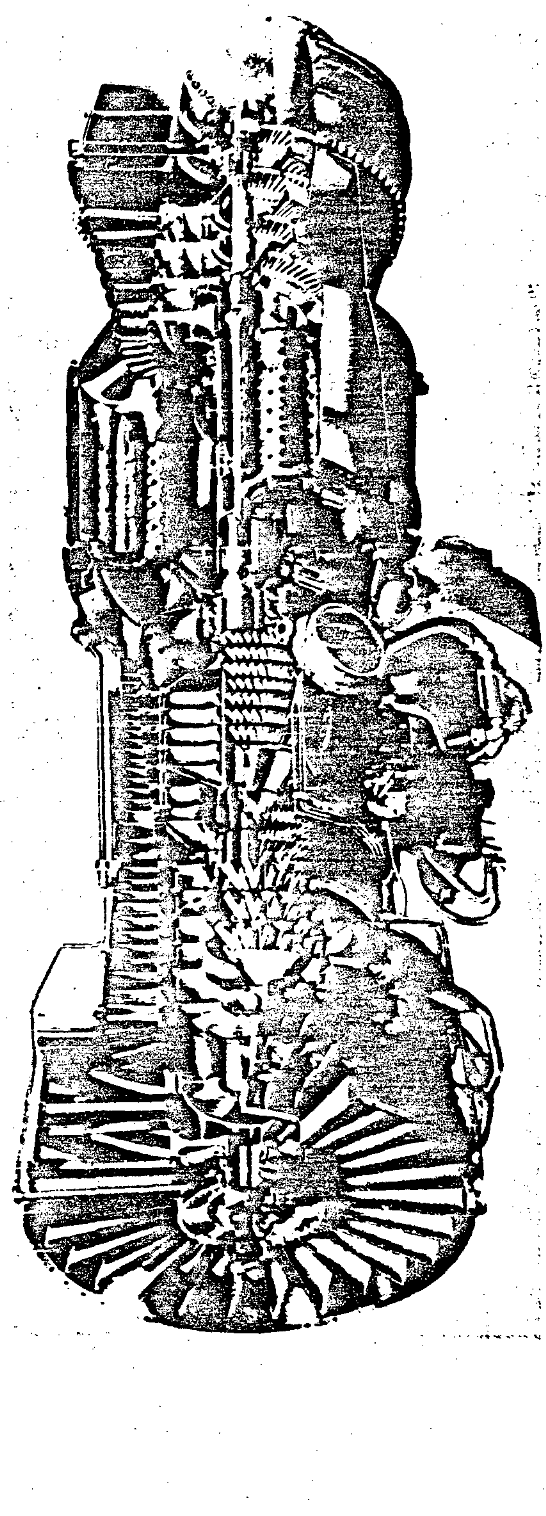

FIGURE 27. CUTAWAY VIEW OF JD3D-1 TURBOFAN ENGINE

The JT3D turbofan engine for commercial use contains approximately 15 per cent (dry weight) of titanium, and the efficient use of titanium goes a long way toward making this engine design possible. The inlet case is fabricated from commercially pure titanium; the fan disks and blades, as well as other disks and blades of the low compressor, are of Ti-6Al-4V alloy; fan disk spacers and fan vane are also of the Ti-6Al-4V alloy. Figure 28 compares the integral fan-low compressor of the JT3D with the conventional JT3C low compressor. The JT3D fan shown here owes its existence as an efficient engineering product to the high strength-density ratio of titanium alloys.

The military version of the JT3D, the TF-33 engine, contains approximately 20 per cent by weight of commercially pure and alloy titanium. Inasmuch as the turbofan will be with us for some time to come, we may expect to see the commercial engine manufacturers follow the pattern of the military engine manufacturers in seeking out weight savings and improvements in operating efficiency.

The advantages of alloy titanium for the intermediate temperature range are superior density-compensated fatigue, yield, and creep strengths compared with heat-treated steels used in United States aircraft engines. Aside from these advantages, there is the lower elastic modulus of titanium, in contrast to steel, which can serve to reduce stress in applications subject to fatigue loading, e.g., compressor blading. A decided "plus" of alloy titanium resides in its superb resistance to atmospheric corrosion, a feature which has contributed much to improved performance in the compressor of the jet engine. The ability of alloy titanium to perform as adequately as steel in the presence of a notch gives it resistance to impact damage, important relative to debris sometimes encountered on aircraft runways. Titanium's ability to perform after heavy damage during flight operations has been demonstrated many times.

The future of titanium for aircraft-engine applications looks very hopeful. The experience of the recent past points to the well-known alloys--commercially pure, Ti-5Al-2.5Sn and Ti-6Al-4V--being more widely used. Evaluation of heat-treated alloys of high strength at moderate temperatures and the high-alpha alloys, such as Ti-8Al-1Mo-1V and Ti-7Al-12Zr, for service up to 1000 F is under way. These developments should do much to give titanium a broader base in the aircraft-engine field.

The Motor Case

The two titanium alloys under consideration for solid-fuel rocket-motor cases are Ti-6Al-4V and beta (13V-11Cr-3Al). By reason of extensive experience with aircraft and aircraft engines, the Ti-6Al-4V alloy could be called the 4340 of titanium alloys available today. It can be readily forged; in the solution-treated, quenched, and aged condition, Ti-6Al-4V develops tensile minima of 155-ksi yield strength, 170-ksi ultimate strength, and 5 per cent elongation. Fusion welding is accomplished using alpha titanium filler (commercially pure or 5Al-2.5Sn) under inert gas. Ti-6Al-4V cases provided a modest gain in strength/weight ratio over present alloy-steel rocket casings. If fracture toughness at high strength-weight ratios were the sole criterion, Ti-6Al-4V alloy would take precedence over the steels.

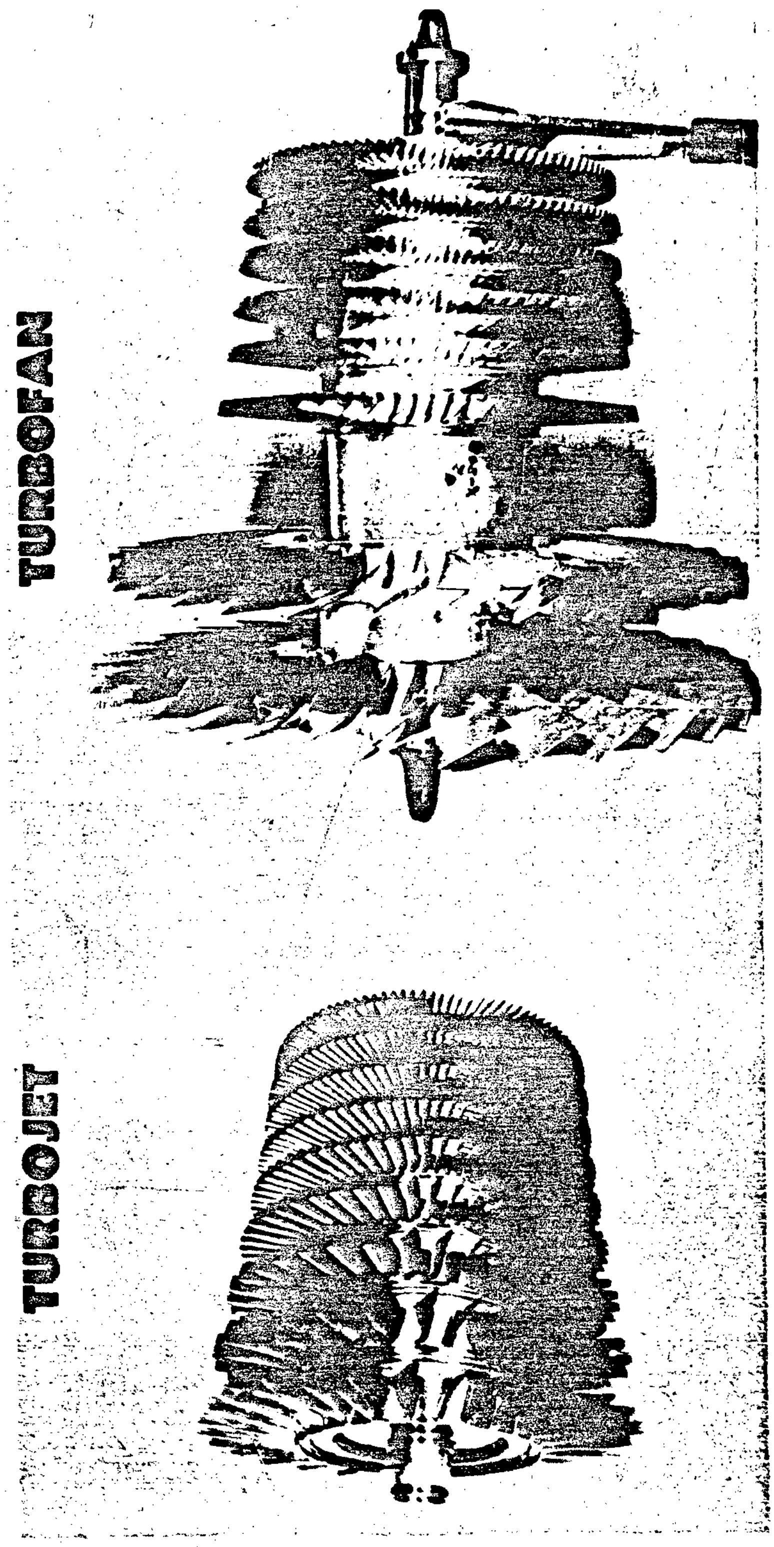

FIGURE 28. COMPARISON OF J57 LOW-COMPRESSOR ROTOR WITH JT3D INTEGRAL FAN - LOW COMPRESSOR ROTOR

An experimental Ti-6Al-4V second-stage missile case weighed 353 pounds, as contrasted with 639 pounds for vacuum-melted steel, and exhibited greatly improved resistance to buckling. Figure 29 shows a Ti-6Al-4V missile fuel tank after pressure testing. The vessel withstood a pressure 20 per cent in excess of the designed strength. Failure was ductile. Ti-5Al-2.5Sn filler wire was used in welding, and the tank was not heat treated beyond annealed properties.

A second-stage missile case fabricated from Ti-6Al-4V is shown in Figure 30. Figure 31 shows a similar case, fabricated from beta alloy (Ti-13V-11Cr-3Al), after burst testing. The beta alloy has a substantially higher strength-to-weight ratio than does Ti-6Al-4V. Work on beta alloy motor cases has been done by Pratt & Whitney, Wright Aeronautical, and Aerojet-General.

The case shown in Figure 31 was produced without longitudinal welds from a flow-turned cylinder welded to forged and drawn end closures. The case material was heat treated, but the welds were not.

At its present stage of development, the beta alloy is more difficult to forge than Ti-6Al-4V. Beta forgings heat treated to high strength levels are somewhat more difficult to machine than those from the lower strength Ti-6Al-4V. Welding of beta alloy is not easy, but it took some years to come up with dependable fusion welds in Ti-6Al-4V. With respect to cold flow (flow turning or shear spinning), the beta alloy appears to be far better than the alpha-beta alloy. At present, beta-alloy cylinders can be generated by cold reductions of 40 per cent without intermediate annealing, whereas Ti-6Al-4V does not respond well to cold flow turning. Ti-6Al-4V cylinders will have to be machined from oversize hot-rolled cylinders unless flow turning at elevated temperatures or the flow turning of solution-treated material becomes practicable.

Table 6 shows the average tensile properties of the first beta-alloy full-scale motor case, for which the target yield strength was 180,000 minimum. The fracture toughness of the full-scale case at 180,000 psi appears adequate, inasmuch as the critical crack length tolerance for 0.080-inch-thick material is 2.1 to 2.4T. The fracture-toughness values for the welds, on the other hand, suggest that further development of welding technique is needed. The relative lack of shear in fast fractures through beta-alloy welds argues for an improvement. Beta welds tend to be coarse grained and show grain-boundary precipitate. Comparing the circumferential uniaxial yield strength of 180,000 psi of the case with the 0.2 per cent biaxial yield strength of 200,000 psi shows that biaxial loading confers an 11 per cent increase. This is in the same order of magnitude as the biaxial kick-up found in Ti-6Al-4V. The inherent 15 to 25 per cent superior strength of beta alloy (density differences taken into account) over Ti-6Al-4V, coupled with an equal biaxial kick-up, makes for an attractive casing material. Burst strengths well in excess of 200,000 psi are definitely attainable. The successful manufacture and pressure testing of a full-scale beta case demonstrates the great potential of the alloy as a casing material.

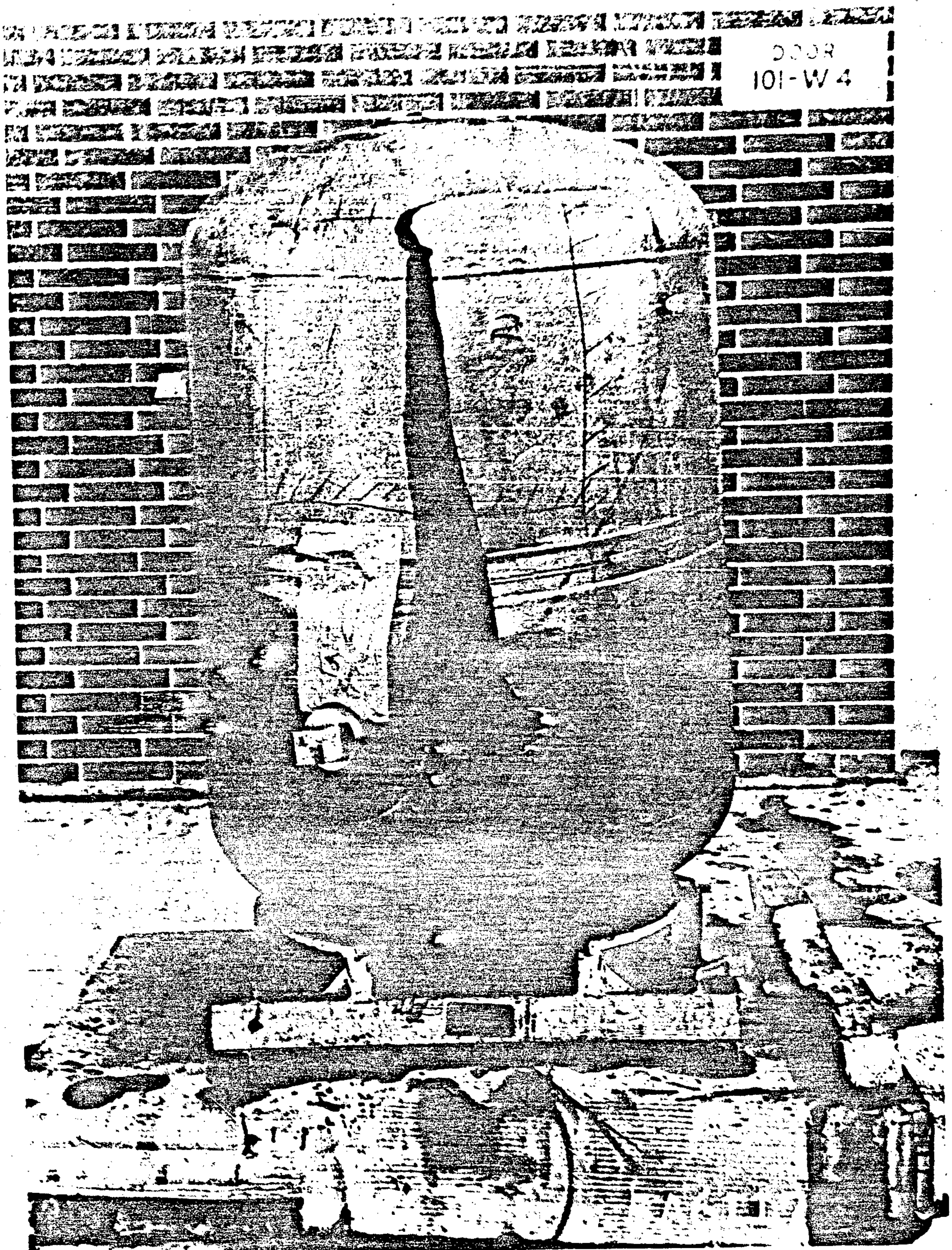

FIGURE 29. BURST-TESTED Ti-6Al-4V PRESSURE VESSEL

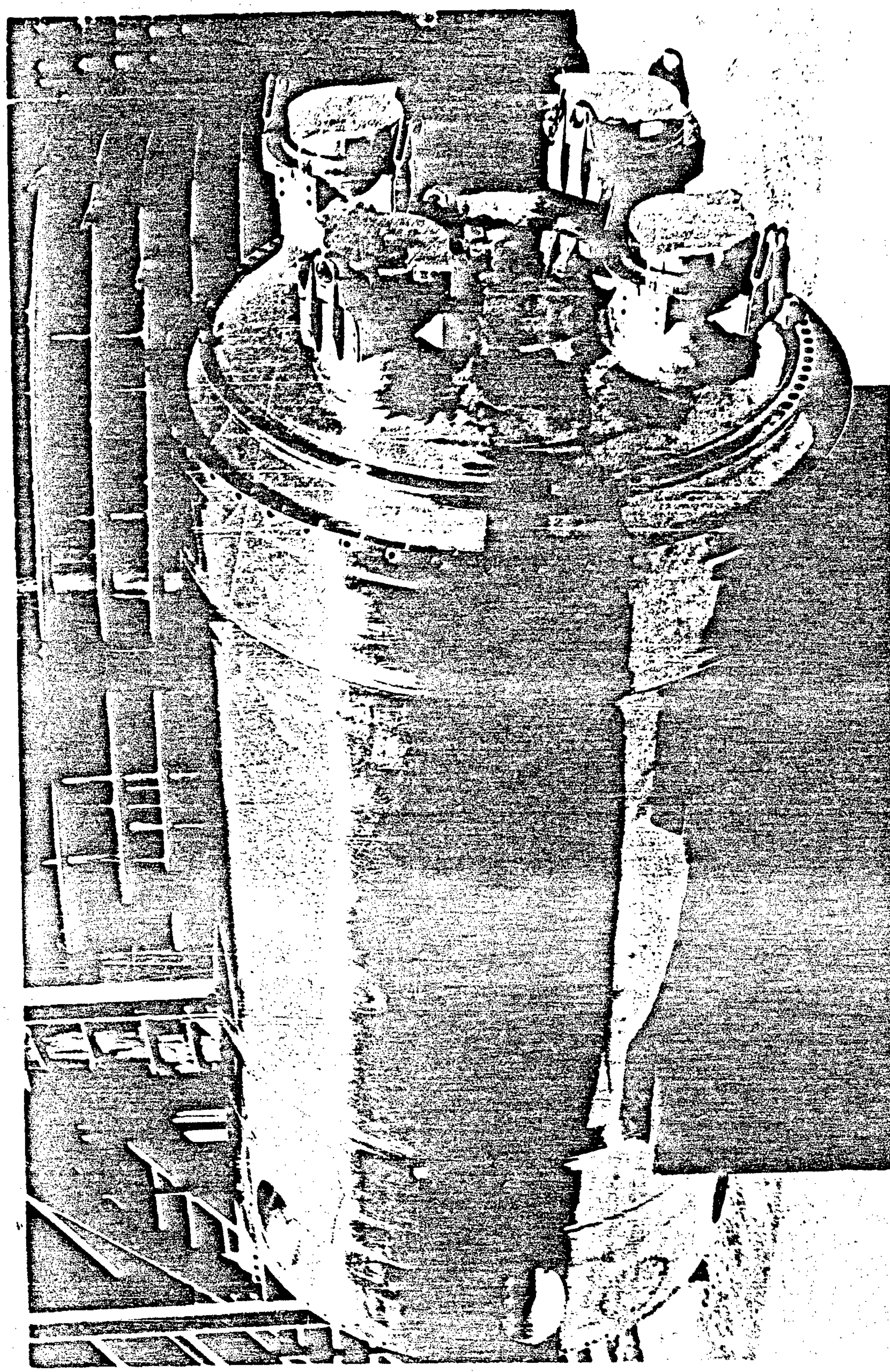

FIGURE 30. SECOND-STAGE MOTOR CASE OF Ti-6Al-4V ALLOY

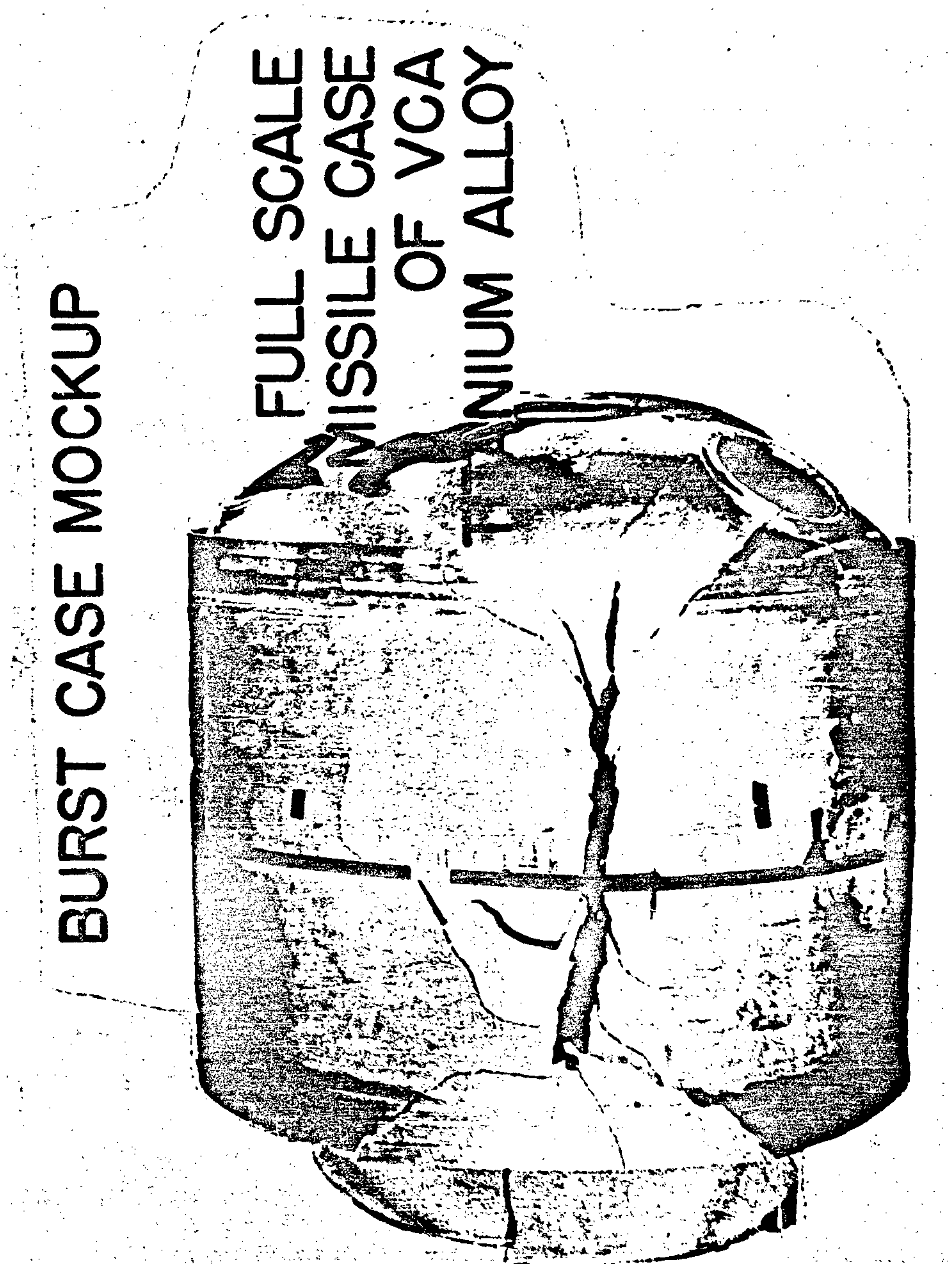

FIGURE 31. BURST FULL-SCALE BETA-ALLOY MISSILE CASE

TABLE 6. MECHANICAL PROPERTIES OF FULL SCALE BETA Ti-13V-11Cr-3Al MISSILE CASE

Part	Direction	Tensile: Ultimate Tensile Strength, ksi	Tensile: 0.2% Offset Yield Strength, ksi	Tensile: Elongation, %	Tensile: Reduction of Area, %
Cylinder	Circumferential	188-195	181-188	4-6	-
Cylinder	Axial	185	174-176	8	-
Front Closure		187-197	181-185	5-7	8-25
Rear Closure		204-209	188-196	5-6	(Bosses)

Fracture Toughness (G_c) in-lb/in.^{2}	
Axial	625-681
Circumferential	297-327

Notch Strength, ksi		
$K_t 8$	Dome	99.5-116
	Cylinder	133-157
$K_t 13$	Dome	83.5-96
	Cylinder	130-140

Pressure Bottles

After the successful development of Ti-6Al-4V helium bottles for the Atlas missile, titanium-alloy pressure bottles have been adopted for many U. S. missiles requiring gas-pressure feed systems. Figure 32 illustrates the Ti-6Al-4V pressure bottles in the Ablestar upper stage. Also shown is the Ti-5Al-2.5Sn alloy nozzle extension. A 96 x 14-inch Ti-6Al-4V pressure bottle used in the X-15 rocket plane is shown in Figure 33. This unit feeds liquid oxygen (LOX) and ammonia at -300 F to the engine. It is of particular interest because of its successful handling of LOX, a pressurized gas in which impact detonation of titanium is possible. In handling LOX under pressure, the titanium surface should be maintained both clean and smooth to reduce the danger of detonation.

The Atlas bottle weighs 75 pounds, compared to the original 205-pound stainless steel bottle. It is manufactured of two hemispheres of Ti-6Al-4V welded together either by inert-gas-shielded arc welding or pressure welding. The arc-welded bottles are heat treated before welding, while the pressure-welded bottles are heat treated after welding. Design stress for the Atlas bottle was 5000 psig at ambient. Burst tests at -320 F have been 9,000 psig and higher.

The Ti-13V-11Cr-3Al beta alloy has been used only to a limited extent in pressure bottles because of its poor cryogenic ductility. It is used for bottles operating under ambient condition or higher. In one application, small (4.4-inch diameter, 14 inch long, 3.5 pound) beta pressure vessels are used to store air at 3,000 psi for general aircraft use. The vessels are manufactured in two pieces by forging, machining, and inert-gas arc welding.

The Future of Titanium in the Aerospace Field

From the foregoing discussion, it is obvious that titanium has a bright future in aeronautical applications. The important questions to consider are the future importance of titanium relative to alternative materials and the effects of other, nonaerospace developments on titanium's role as an aerospace material. It is appropriate, therefore, to speculate on the ultimate growth of the titanium industry and on the effects that this growth may have on price and the ultimate position of titanium.

Titanium cannot, over the next decade, continue its current growth rate of roughly doubling production every 2 years. Industry spokesmen, however, forecast a production of the order of 50,000,000 pounds of mill products by 1970. At least 50 per cent should go into aeronautical applications. Industry forecasts of the titanium market by 1980, have been as high as 250,000,000 to 500,000,000 pounds of mill products. At these rates of production, the price of titanium products is estimated at roughly twice that of corresponding stainless steel products.

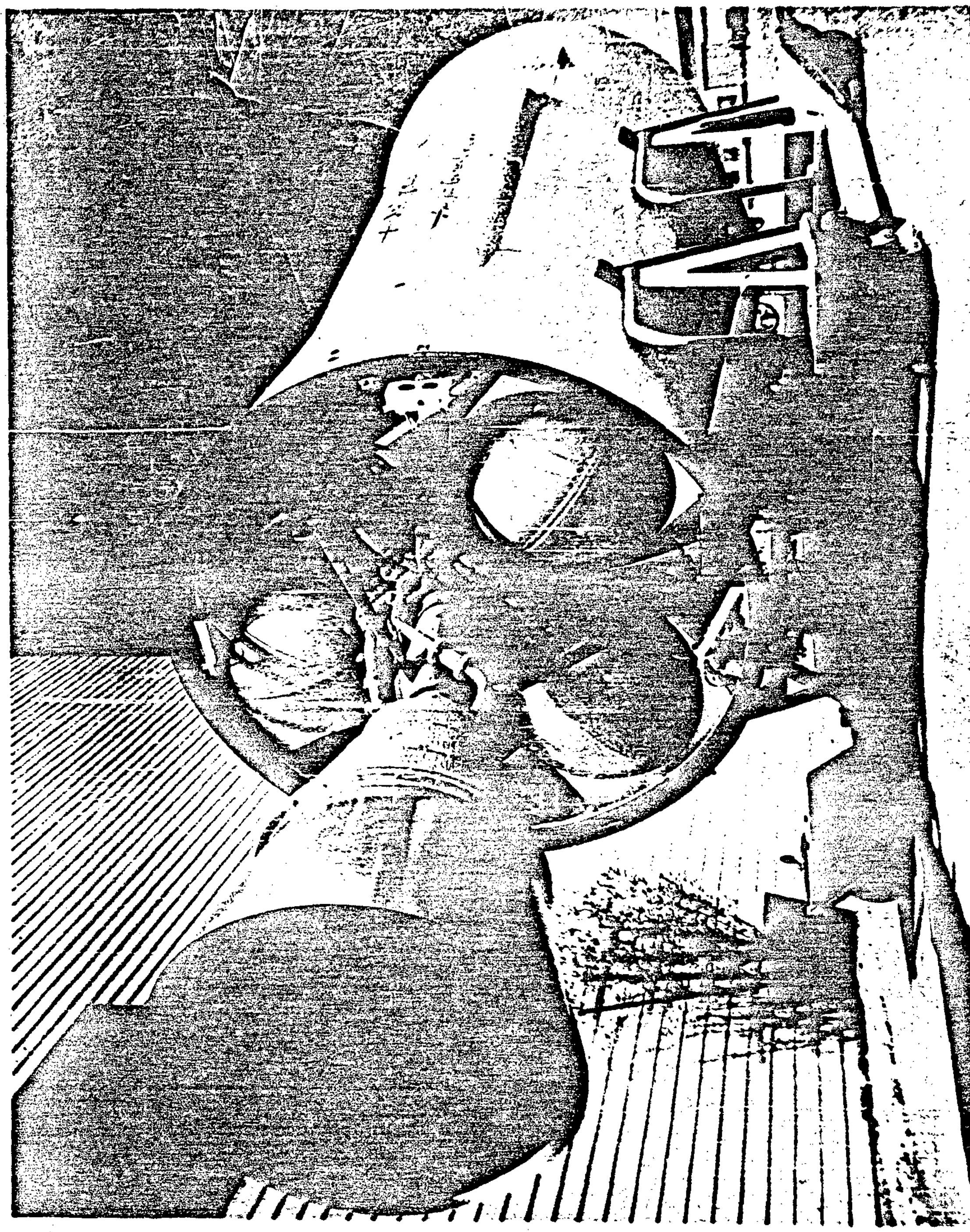

FIGURE 32. Ti-6Al-4V PRESSURE BOTTLES AND Ti-5Al-2.5Sn NOZZLE EXTENSION IN ABLESTAR UPPER STAGE

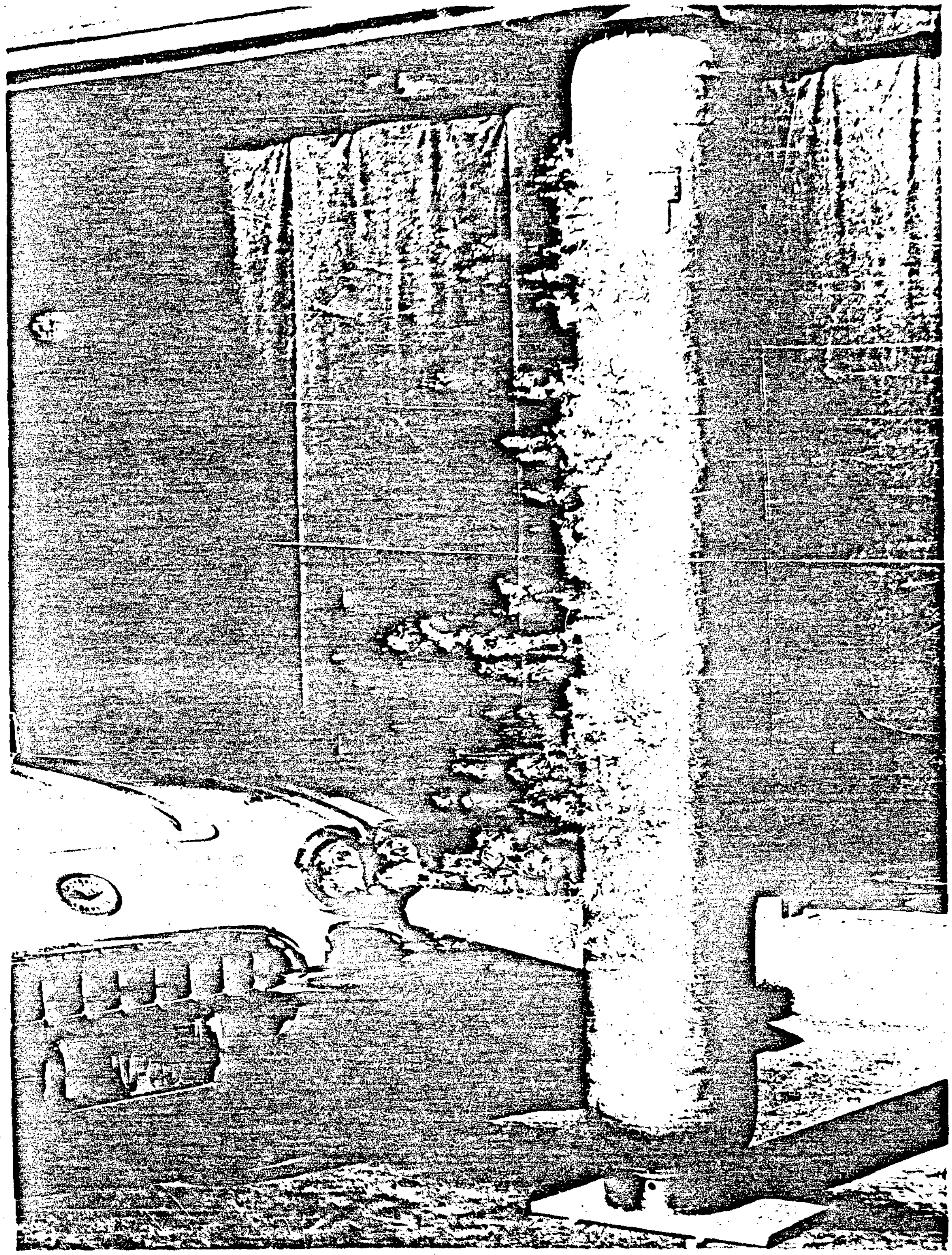

FIGURE 33. LIQUID-OXYGEN PRESSURE BOTTLE OF Ti-6Al-4V ALLOY IN THE X-15 ROCKET PLANE

In airframe applications we may expect to see, by reason of price reductions, increasing application of titanium in the current generation of subsonic and supersonic aircraft. Supersonic transports operating at about Mach 2.5 should be in production by 1970; titanium may be expected to replace aluminum as the major structural material for this type of aircraft. VTOL and STOL aircraft will call for improved strength/weight ratios, and titanium is the obvious means toward this goal.

Because of its higher performance and efficiency, the turbofan will have a dominant role in power for commercial and military transports for some time to come. Titanium up to 20 per cent on a dry-weight basis, is a reality; as titanium becomes more competitive with steel, increasing application of titanium may be expected. Engines for aircraft up to Mach 3 will make limited use of titanium. Above Mach 3 titanium may be expected to be replaced by steels or nickel-base alloys, subject to change, however, as titanium alloys of higher temperature capability are developed.

Probably by 1970-1975, recoverable boosters ought to be used in the missile field. These might use appreciable titanium, since they would attain about Mach 3 on re-entry. Titanium cases for solid-propellant rocket motors should continue to meet considerable competition from reinforced glass fibers. However, second-stage cases requiring improved buckling stability should result in a substantial position for titanium in the motor-case field. Use of titanium as a container for pressurized gases should increase considerably through high-strength titanium bottles for containing compressed air and other gases at ambient conditions, in addition to its current position as a cryogenic gas container. Concerning cryogenic applications, titanium is expected to play a dominant role in containing liquid hydrogen, an important fuel for large rocket boosters. Liquid oxygen will remain a doubtful application because of the detonation problem unless means are found to minimize ignition under impact. While the number of space vehicles to be built is difficult to forecast, titanium was important in the structure of the Mercury capsule and is expected to play an important role in the Apollo three-man space ship.

Nonaeronautical applications will increase markedly as titanium's production increases and price decreases. At maturity, it is expected that the annual market for titanium mill products in the chemical-process equipment industry may be as high as 5,000,000 to 10,000,000 pounds. Also, considerable titanium application is expected in steam turbines (blades), automotive turbines, and various parts of conventional automotive engines. As these applications build up from the present 3 to 5 per cent to 30 to 50 per cent of the titanium market, the aeronautical and aerospace fields should be benefited in price and availability of titanium mill products.

LIST OF DMIC MEMORANDA ISSUED

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Copies of the technical memoranda listed below may be obtained from DMIC at no cost by Government agencies and by Government contractors, subcontractors, and their suppliers. Others may obtain copies from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

A list of DMIC Memoranda 1-90 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
91	The Emittance of Titanium and Titanium Alloys, March 17, 1961, (PB 161241 $0.50)
92	Stress-Rupture Strengths of Selected Alloys, March 23, 1961, (AD 255075 $0.50)
93	A Review of Recent Developments in Titanium and Titanium Alloy Technology, March 27, 1961, (PB 161243 $0.50)
94	Review of Recent Developments in the Evaluation of Special Metal Properties, March 28, 1961, (PB 161244 $0.50)
95	Strengthening Mechanisms in Nickel-Base High-Temperature Alloys, April 4, 1961, (PB 161245 $0.50)
96	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, April 7, 1961, (PB 161246 $0.50)
97	Review of Recent Developments in the Technology of Columbium and Tantalum, April 10, 1961, (PB 161247 $0.50)
98	Electropolishing and Chemical Polishing of High-Strength, High-Temperature Metals and Alloys, April 12, 1961, (PB 161248 $0.50)
99	Review of Recent Developments in the Technology of High-Strength Stainless Steels, April 14, 1961, (PB 161249 $0.50)
100	Review of Current Developments in the Metallurgy of High-Strength Steels, April 20, 1961, (PB 161250 $0.50)
101	Statistical Analysis of Tensile Properties of Heat-Treated Mo-0.5Ti Sheet, April 24, 1961, (AD 255456 $0.50)
102	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, April 26, 1961, (AD 255278 $0.50)
103	The Emittance of Coated Materials Suitable for Elevated-Temperature Use, May 4, 1961, (AD 256479 $2.75)
104	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, May 5, 1961, (AD 255659 $0.50)
105	Review of Recent Developments in the Metallurgy of Beryllium, May 10, 1961, (AD 256206 $0.50)
106	Survey of Materials for High-Temperature Bearing and Sliding Applications, May 12, 1961, (AD 257408 $2.00)
107	A Comparison of the Brittle Behavior of Metallic and Nonmetallic Materials, May 16, 1961, (AD 258042 $0.50)
108	Review of Recent Developments in the Technology of Tungsten, May 18, 1961, (AD 256633 $0.50)
109	Review of Recent Developments in Metals Joining, May 25, 1961, (AD 256852 $0.50)
110	Glass Fiber for Solid-Propellant Rocket-Motor Cases, June 6, 1961
111	The Emittance of Stainless Steels, June 12, 1961
112	Review of Recent Developments in the Evaluation of Special Metal Properties, June 27, 1961
113	A Review of Recent Developments in Titanium and Titanium Alloy Technology, July 3, 1961

LIST OF DMIC MEMORANDA ISSUED
(Continued)

DMIC Memorandum Number	Title
114	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, July 5, 1961
115	Review of Recent Developments in the Technology of Columbium and Tantalum, July 7, 1961
116	General Recommendations on Design Features for Titanium and Zirconium Production-Melting Furnaces, July 19, 1961
117	Review of Recent Developments in the Technology of High-Strength Stainless Steels, July 14, 1961
118	Review of Recent Developments in the Metallurgy of High-Strength Steels, July 21, 1961
119	The Emittance of Iron, Nickel, Cobalt and Their Alloys, July 25, 1961
120	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, July 31, 1961
121	Fabricating and Machining Practices for the All-Beta Titanium Alloy, August 3, 1961
122	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, August 4, 1961
123	Review of Recent Developments in the Technology of Beryllium, August 18, 1961
124	Investigation of Delayed-Cracking Phenomenon in Hydrogenated Unalloyed Titanium, August 30, 1961
125	Review of Recent Developments in Metals Joining, September 1, 1961
126	A Review of Recent Developments in Titanium and Titanium Alloy Technology, September 15, 1961
127	Review of Recent Developments in the Technology of Tungsten, September 22, 1961
128	Review of Recent Developments in the Evaluation of Special Metal Properties, September 27, 1961
129	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, October 6, 1961
130	Review of Recent Developments in the Technology of Columbium and Tantalum, October 10, 1961
131	Review of Recent Developments in the Technology of High-Strength Stainless Steels, October 13, 1961
132	Review of Recent Developments in the Metallurgy of High-Strength Steels, October 20. 1961